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Fly Ash Conditioning with Sulfur Trioxide

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FLY ASH CONDITIONING WITH SULFUR TRIOXIDE

Industrial Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

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FLY ASH CONDITIONING WITH SULFUR TRIOXIDE

by

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The report describes an evaluation of an SO3 injection system for the George Neal Unit 2 boiler of the Iowa Public Service Co. in Sioux City, Iowa. Results of base line tests without conditioning indicate a dust resistivity of 6 x 10 to the 12th power ohm-cm at 118C: the precipitatcs's average collection efficiency was 91.3% at a specific collecting area of 42.8 sq m/ cu m/sec). Because transformer-rectifier sets tripped out, apparently due to ash build-up in the hoppers, only one precipitator effeciency test was conducted with the SO3 system operating continously with all T-R sets operating. Results of this test were: (1)specific collecting area=41.8 sq m/ (cu m/sec); (2) collection effeciencies =99.27% (ASME method), 98.96% (EPA method) and 98.78% (EPA method, including first impinger residue); and (3) 4x10 to the 10th power ohm-cm dust resistivity at 143C. An adequate accounting was made for the fat e of the injected SO3.

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I. INTRODUCTION AND SUMMARY

This report describes a study conducted by Southern Research Institute for the purpose of evaluating an SO_3 injection system for the George Neal Unit 2 Boiler of Iowa Public Service Company in Sioux City, Iowa. The SO_3 injection system was supplied by Research Cottrell for the purpose of increasing the collection efficiency of the electrostatic precipitator installed on the subject boiler. The study was sponsored jointly by Iowa Public Service Company and the Industrial Environmental Research Laboratory of the Environmental Protection Agency. Mass loading determinations were conducted by Research Cottrell and Kin Associates. EPA's portion of the study was concerned primarily with accounting for the fate of the injected conditioning agent with emphasis on stack losses of SO_3, whereas IPS's objective was to determine whether the injection system would provide a means of reliably increasing the precipitator collection efficiency to 99% at full load with normal plant operating conditions. A second objective of IPS was to obtain an estimate of the specific collecting area which would be required to achieve 99.0% collection efficiency without conditioning when the precipitator is collecting fly ash produced from the low sulfur, low sodium western coal which is used for fuel at this installation.

The study consisted of a two-phase test program that was followed by appropriate laboratory measurements and analyses. The two phases of the test program were: (1) An evaluation of precipitator performance at full load without SO_3 injection. These tests were conducted on March 27, 1976. (2) An evaluation of precipitator performance at full load with SO_3 injection. These tests were conducted during the week of May 17, 1976.

Results from the baseline tests on March 27 indicated that, as expected, precipitator performance was limited by the high electrical resistivity of the collected dust. The average collection efficiency reported by Research Cottrell was 91.3% at a plant load of

299 megawatts. Measurements with a point-plane probe indicated a dust resistivity value of approximately 6×10^{12} ohm-cm at 118°C (245°F). Voltage-current relationships obtained from the TR sets also exhibited behavior typical of precipitators collecting high resistivity dust. These voltage-current relationships were used to estimate the allowable electrical operating conditions which could be maintained without back corona or excessive sparking in the absence of SO_3 conditioning. The estimated electrical operating conditions, the precipitator geometry, and the measured particle size distributions at the precipitator inlet were used as input data to a computer program which simulates the operation of the precipitator. The computer program was then used to estimate the specific collecting area that would be required to achieve 99.0% collecting efficiency. If it is assumed that the enlarged precipitator should include a sufficient safety margin to allow about 12% of the collecting area to be de-energized without decreasing performance below 99% collection efficiency, the program output indicates that a specific collecting area of 108 $m^2/(m^3/sec)$ (550 $ft^2/1000$ ACFM) would suffice.

The test program with SO_3 injection was not conducted in accordance with our original test plan because of difficulties with the SO_3 injection system and the precipitator TR sets "tripping out". It is our understanding that the cause of the difficulty with the TR sets was ash build-up in the hoppers. As a result of these problems, only one efficiency test at a load of 300 MW was obtained with the SO_3 injection system operating continually and without transformer-rectifier failures. The results obtained were as follows:

Test at Stack	Outlet Dust Concentration, gm/m^3 (gr/ACF)	Precipitator Efficiency %
ASME	0.0508(.0222)	99.27
EPA	0.0703(.0307)	98.96
EPA with residue from first impinger	0.0828(.0362)	98.78

These results were obtained from the Kin Associates report concerning the subject test program, and the precipitator efficiencies are based on an inlet dust concentration of 10.38 gm/DNm^3 at 21°C (70°F) (4.536 gr/DSCF). Although the above data indicate the performance of the precipitator was approaching the desired value of 99%, additional test data taken after the injection system and precipitator have operated under reasonably steady-state conditions for several days would be required to determine if 99% collection efficiency can be consistently maintained. This will require a solution to the ash build-up problem and also a turn-down capability for the SO_3 system. The reported rate of SO_3 injection during the test period was about 25 ppm by volume.

Our conclusions with regard to the effect of SO_3 injection at this rate on the flue gas and fly ash properties, and the precipitator performance, may be summarized as follows:

(1) Dust resistivity values measured with the point-plane probe indicated that resistivity decreased to approximately 4×10^{10} ohm-cm at 143°C (290°F).

(2) Voltage-current curves obtained from the precipitator power supplies indicated that the dust resistivity was not limiting the electrical operating conditions. The electrical operating conditions with SO_3 conditioning, the precipitator geometry, and the measured inlet size distribution were used as input data to the mathematical model. The results indicated that a collection efficiency of greater than 99% is theoretically possible with a specific collecting area of 39.37 m^2/(m^3/sec) (200 ft^2/1000 ACFM) and with the improved voltages and currents.

(3) At the inlet of the precipitator, where the gas temperature averaged 128°C (262°F), about 2 ppm of the added SO_3 was found in the gas phase, and about 23 ppm was found on the suspended fly ash. Ash samples were collected and fractionated by size in a series of cyclones; variations in the sulfate content of different samples may have been caused by fluctuations in either boiler load (total gas flow) or SO_3 injection rate. Ash of smaller particle size contained

higher weight-percentage of sulfate than ash of larger size, as expected.

(4) In the precipitator hoppers adjacent to the center line through the precipitator, about 15 ppm of the injected SO_3 was found as sulfate on the ash. This quantity of SO_3 was lower than expected from other data (SO_3 injection rate and SO_3 found as sulfate on ash at the inlet and outlet). The discrepancy presumably was caused by a lower-than-average rate of SO_3 injection in nozzles directly upstream from the hoppers in question.

(5) At the outlet of the precipitator, where the gas temperature averaged 118°C (244°F), less than 1 ppm of H_2SO_4 vapor was found in the gas stream, and only about 2 to 3 ppm of SO_3 was found as sulfate on the ash. The H_2SO_4 vapor concentration was too low to be distinguished from that occurring without conditioning. The total sulfate on the outlet ash was only about 50% of the value found without conditioning. Even though the weight fraction of sulfate on the ash was increased by conditioning, the product of (1) sulfate fraction and (2) total ash concentration was lower with conditioning than without, because of the marked increase in precipitation efficiency. In other words, the decrease in factor (2) as the result of conditioning was more important than the increase in factor (1).

In summary, the data indicate that an adequate accounting was made for the fate of the injected SO_3 and that the overall rate of SO_3 emission from the stack (counting both H_2SO_4 vapor and sulfate on the ash) was lower with conditioning than without. Additional testing will be required to determine whether the injection system can enable 99% collection efficiency of fly ash in the precipitator to be reliably achieved.

II. BACKGROUND

Collection efficiency measurements on the electrostatic precipitator installed on Unit 2 of the George Neal Station have indicated that the precipitator performance is appreciably below the design value of 99% at full load conditions. Although the precipitator performance has in the past reportedly been limited by factors other than dust resistivity (specifically, a poor gas velocity distribution and hopper sweepage), both the electrical readings of transformer-rectifier sets and in situ resistivity measurements have shown that the electrical operating characteristics are severely limited by dust resistivity.

In order to achieve the design value for collection efficiency at this installation, two options are feasible: (a) increase the plate area of the precipitator, and (b) lower the dust resistivity to the extent that it does not limit the performance of the unit. Option (a) involves a large capital expenditure since it is estimated that the total plate area would have to be increased by a factor of about 3 in order to achieve 99% collection efficiency. The precipitator currently is designed for a gas flow of 512.48 m^3/sec at 129°C (1,086,000 ACFM at 263°F), and the existing plate area is 19,906 m^2 (214,272 ft^2). This gives a design specific collecting area of 38.84 $m^2/(m^3/sec)$ or 197 ft^2/1000 ACFM. In view of the expense required to enlarge the existing unit the required amount, Iowa Public Service decided to evaluate the use of an SO_3 injection system for the purpose of lowering ash resistivity and increasing the precipitator performance.

The SO_3 injection system was supplied and operated by Research Cottrell. The system burns molten sulfur to produce SO_2 which is subsequently oxidized to SO_3 in a catalytic reactor. The gas leaving the converter is transported to the precipitator inlet duct through an insulated line, and injection into the flue gas is accomplished with an insulated manifold. The system is designed with the objective of maintaining the temperature in the transport line and

in the manifold above the H_2SO_4 dewpoint. The design details of the SO_3 system are not provided in this report as a result of a confidentiality agreement with Research Cottrell.

III. RESULTS FROM TEST PROGRAM

A. Particle Size Measurements

Particle size measurements were conducted during both the baseline and SO_3 injection tests with cascade impactors and cyclones. The purpose of the cascade impactor measurements was to provide size distribution data for subsequent use in a mathematical model which was employed to simulate the operation of the precipitator during the test program. Multistage cyclones were used primarily to obtain size fractionated samples for chemical analysis, and results from these measurements will be presented in the section on chemical analyses.

During the baseline test series (March 27), a total of eight Brink cascade impactor runs were performed at the precipitator inlet, and two Andersen impactor runs were performed at the outlet. Useful data were not obtained from the outlet runs because of substrate sticking and stage overloading. Inlet impactors runs were made with four-point traverses in which two points were approximately 0.3 meter (1 ft) apart at the top of the duct and the other two points were the same distance apart at the center of the duct. The traverses were conducted in port Nos. 2, 4, 5, and 7 (See Figure 20). Figure 1 gives the data obtained from the March 27 inlet series on log probability co-ordinates, and Figure 2 presents the distribution in terms of cumulative mass loadings as a function of particle diameter.

The second series of particle size measurements was conducted the week of May 17, 1976. A total of sixteen Brink impactor runs were conducted on May 18, 19, 20, and 21 using the same traversing procedure described above. Outlet Andersen impactor runs were also conducted on May 19, 20, and 21, but only the data obtained on May 19 are of interest because of problems encountered with the precipitator or the injection system on the other test days. Figures 3 and 4 give the average inlet size distribution on log probability

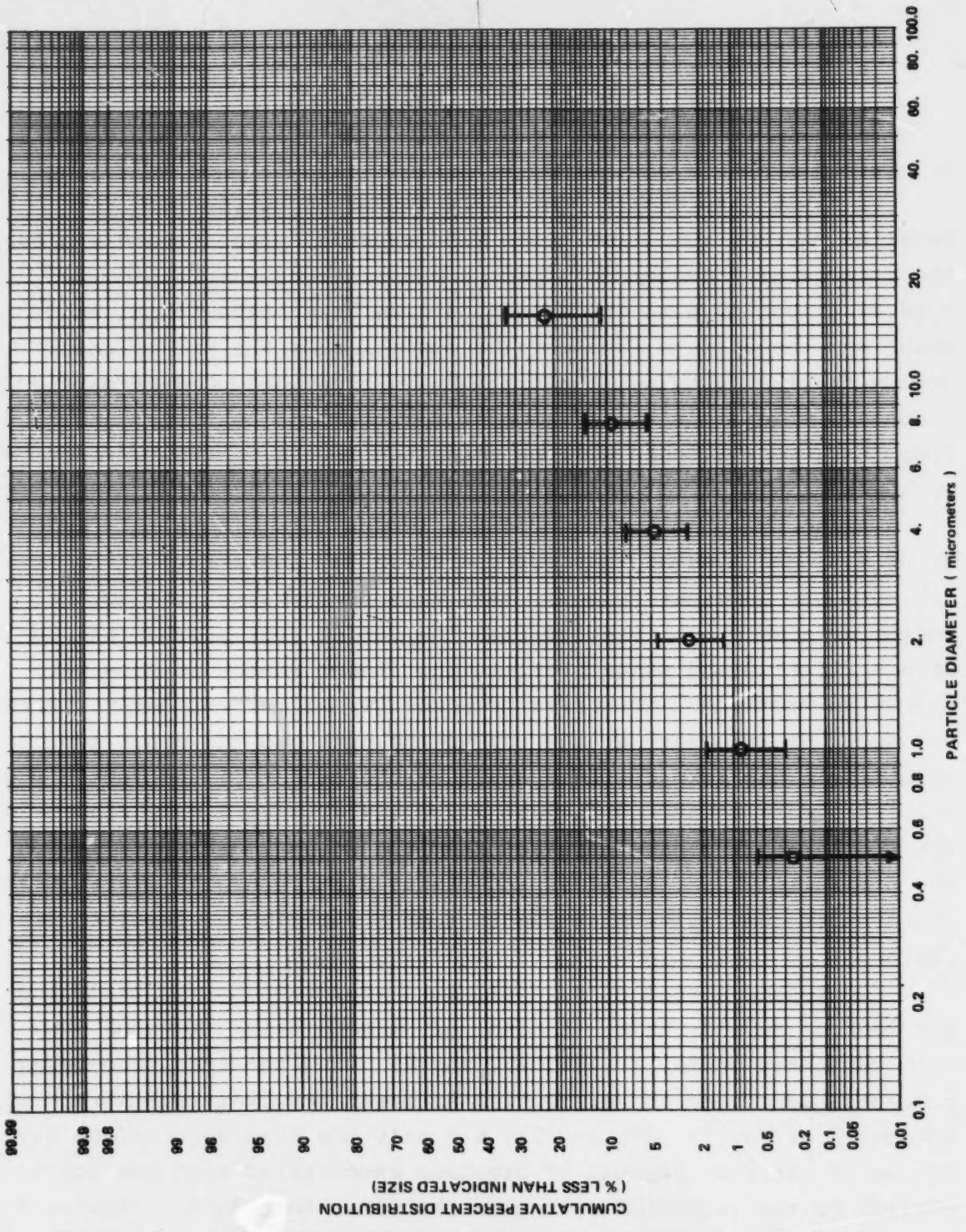

Figure 1. Inlet Size Distribution (Cumulative Percent) for March 27, 1976 with 90% Confidence Intervals

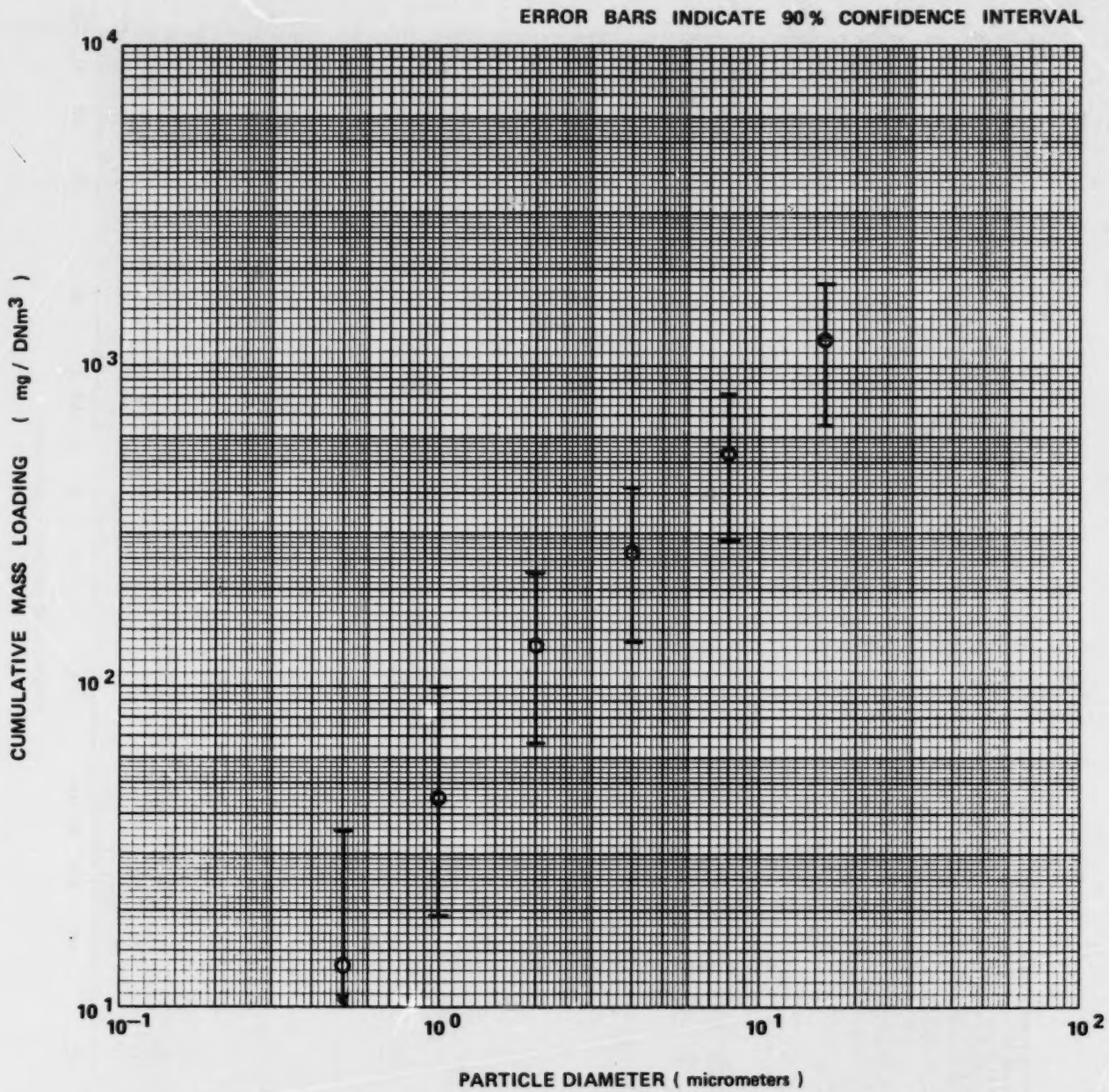

Figure 2. Inlet Size Distribution (Cumulative Mass) for March 27, 1976 with 90% Confidence Intervals

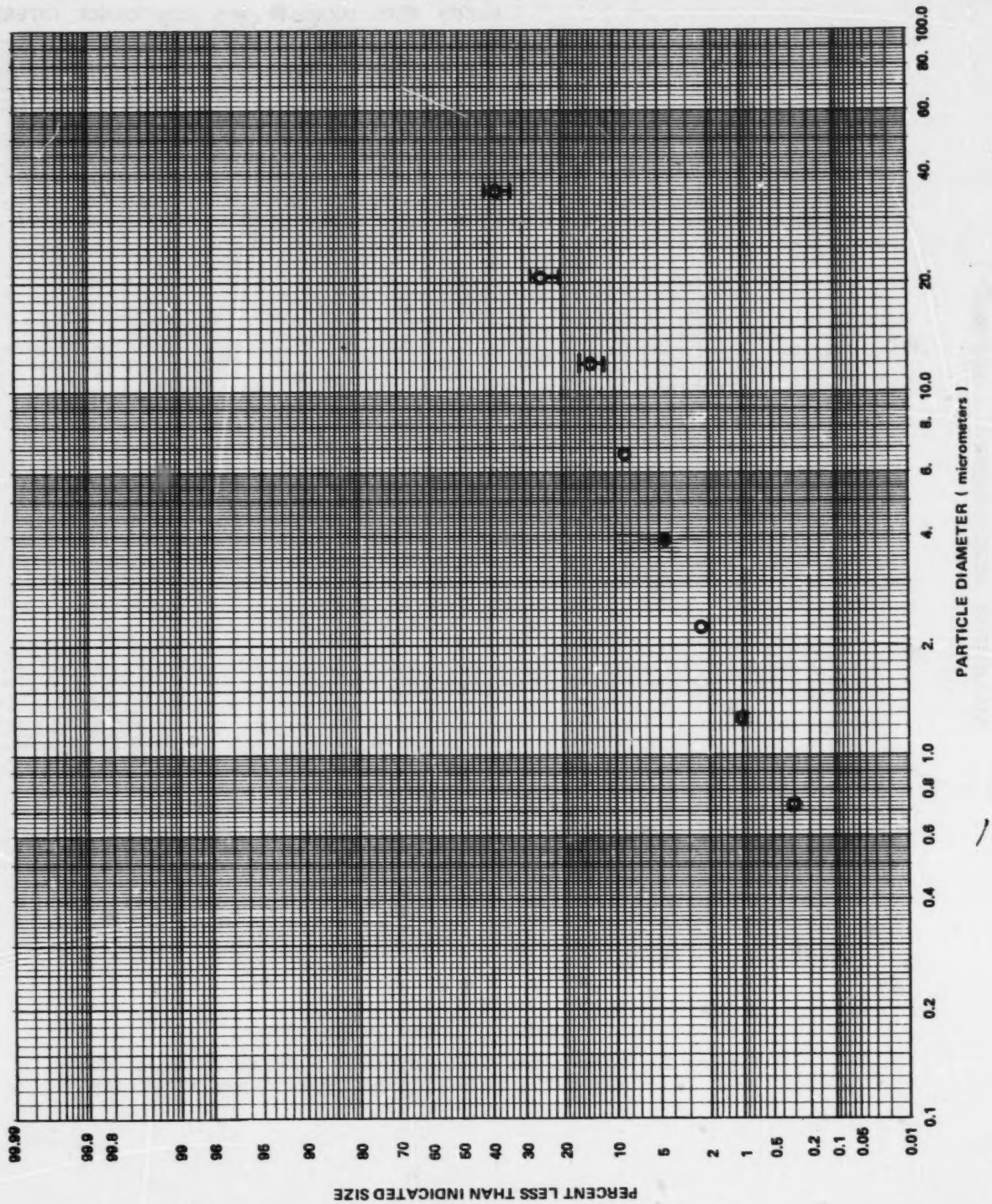

Figure 3. Average Inlet Size Distribution (Cumulative Percent) for May 18-21, 1976 with 90% Confidence Intervals

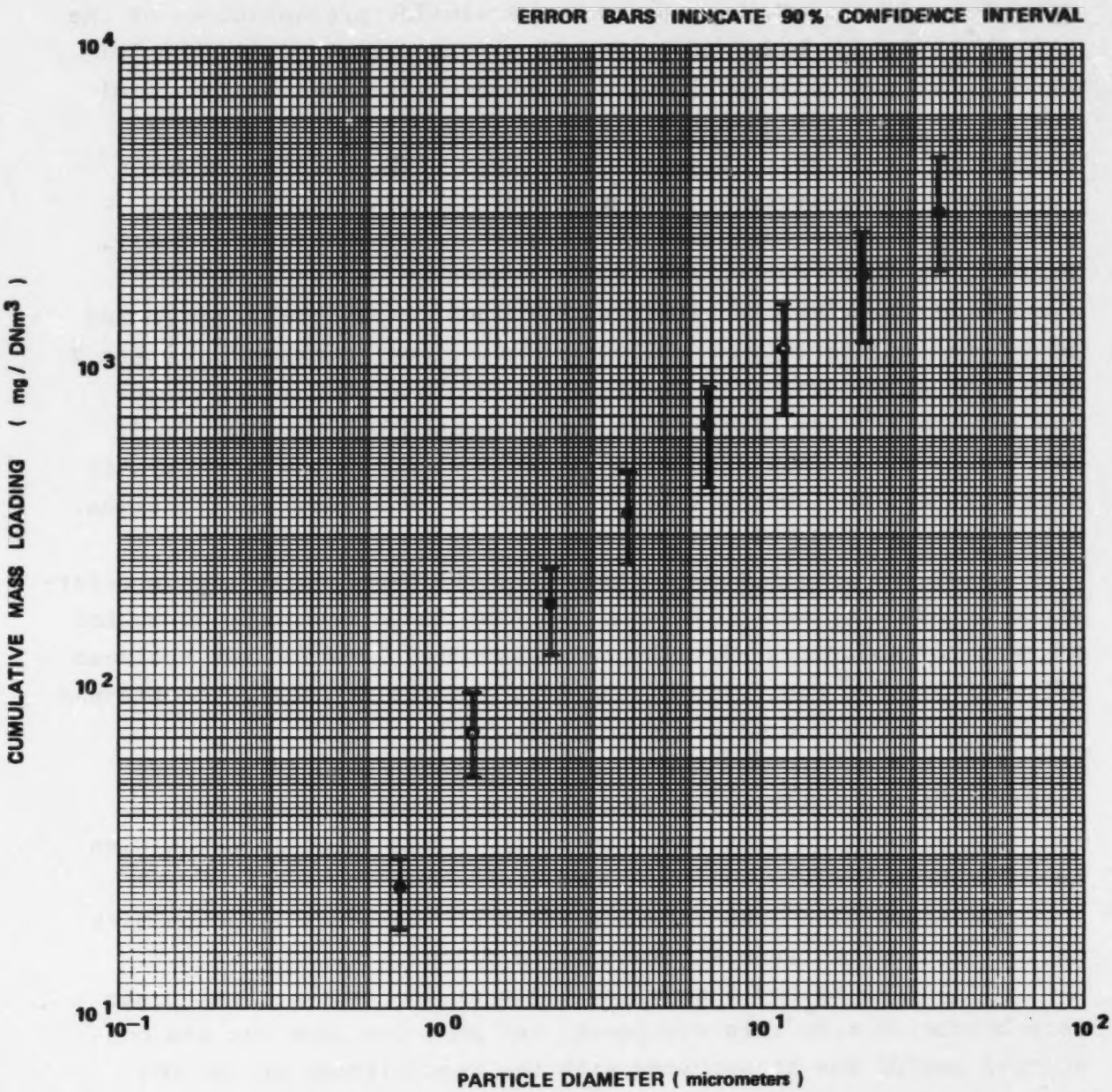

Figure 4. Average Inlet Size Distribution (Cumulative Mass) for May 18-21, 1976 with 90% Confidence Intervals

co-ordinates and in terms of cumulative mass loading for the time period May 18-21. Figures 5 and 6 are similar presentations of the size distribution obtained on May 19 at the outlet of the precipitator. The cumulative percent distribution is based on the total outlet mass loading obtained with the impactor (35.45 mg/DNm^3). Because of the almost 10 meter (32.8 feet) depth of the outlet duct work, full traverses were impractical. Therefore, single point sampling was performed at a depth of 2.4 meters (7.8 feet). This single point outlet size distribution, together with the average of the size distributions obtained on May 18-21, were used to compute the fractional collection efficiencies shown in Figure 7. Note that a comparison of Figure 1 and 3 shows that essentially the same inlet size distribution was obtained for the March and May test series. The data from Figure 4 were used in the computer model projections, which will be discussed in a subsequent section.

B. Mass Train Results

Inlet and outlet mass loadings for the baseline test were determined by Research Cottrell using the ASME Power Test Code 27 method on March 27 and March 28. The inlet sampling location was upstream of the injection manifold (Figure 20), and outlet data were obtained in the stack. These data are given in Table 1.

Mass train data during the SO_3 injection tests in May were obtained by Kin Associates, Inc. using the following methods:

(1) A modified ASME sampling train at the inlet location with an in-stack filter.

(2) A modified ASME sampling train at the stack location with an in-stack Gelman type AE glass fiber filter.

(3) An EPA Method 5 sampling train at the stack. Four tests were conducted with this equipment, but only one data set was considered useful due to problems with the precipitator or the SO_3 injection system. The tests were designated as follows:

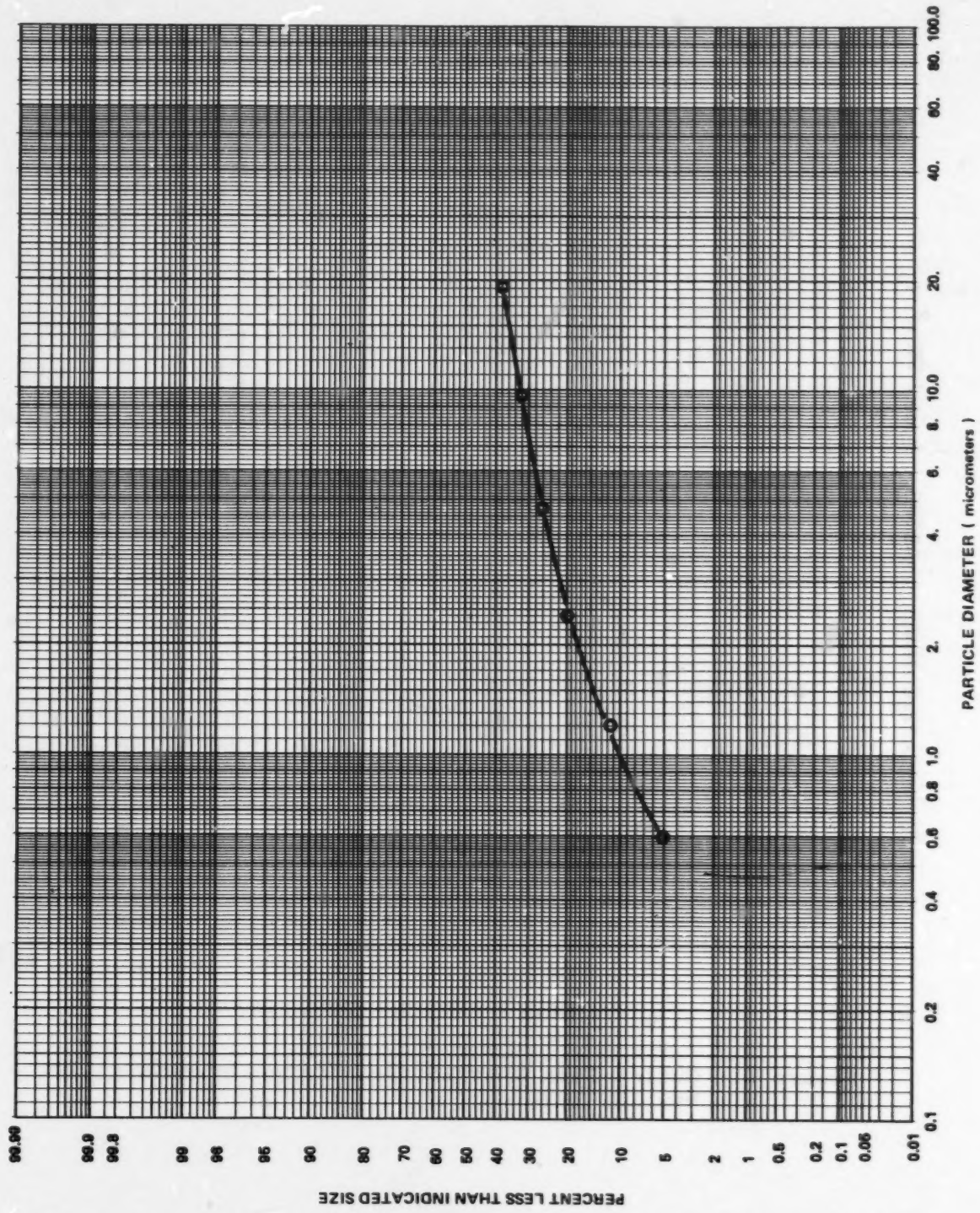

Figure 5. Outlet Size Distribution (Cumulative Percent) for May 19, 1976

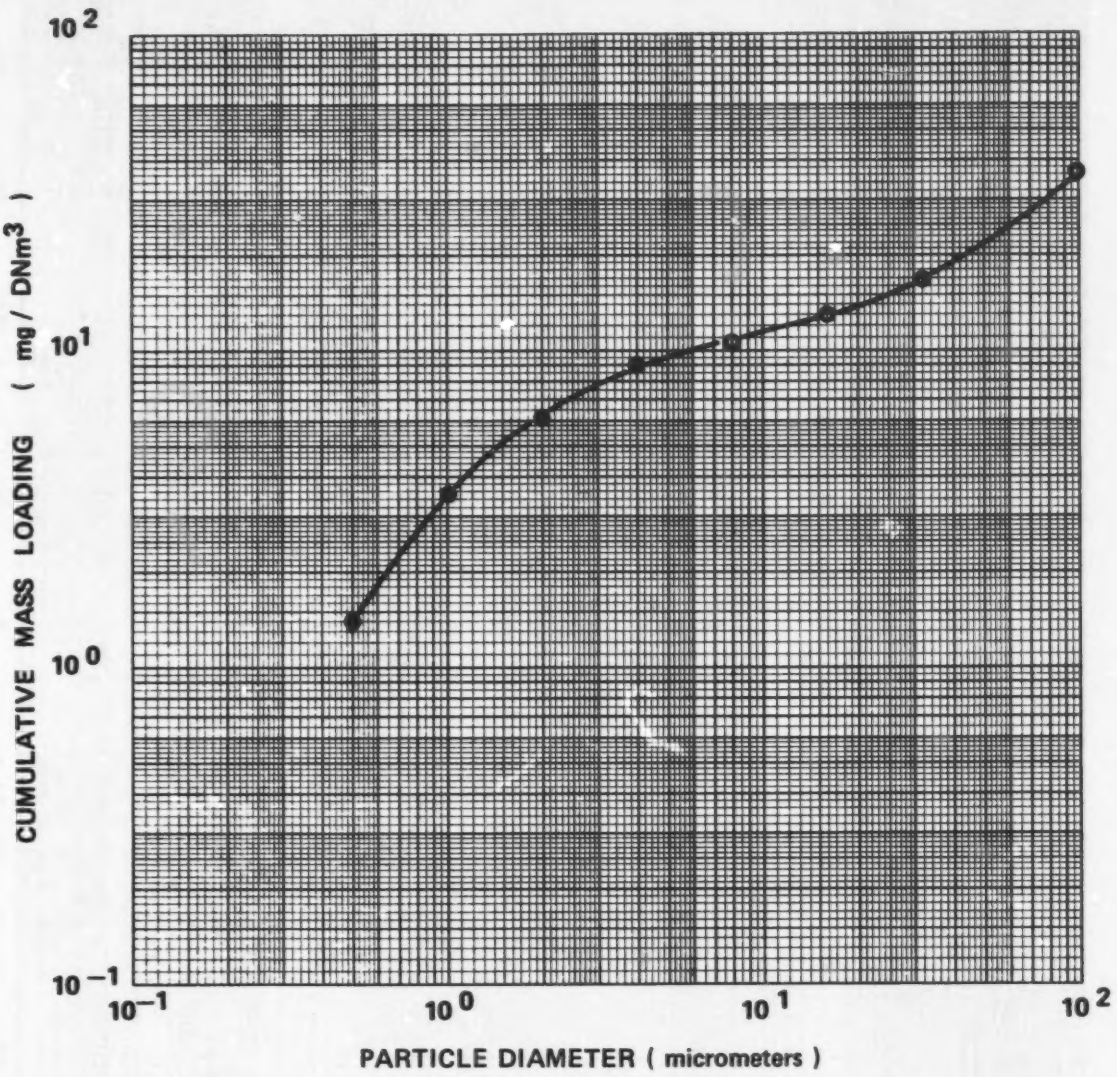

Figure 6. Outlet Size Distribution (Cumulative Mass) for May 19, 1976

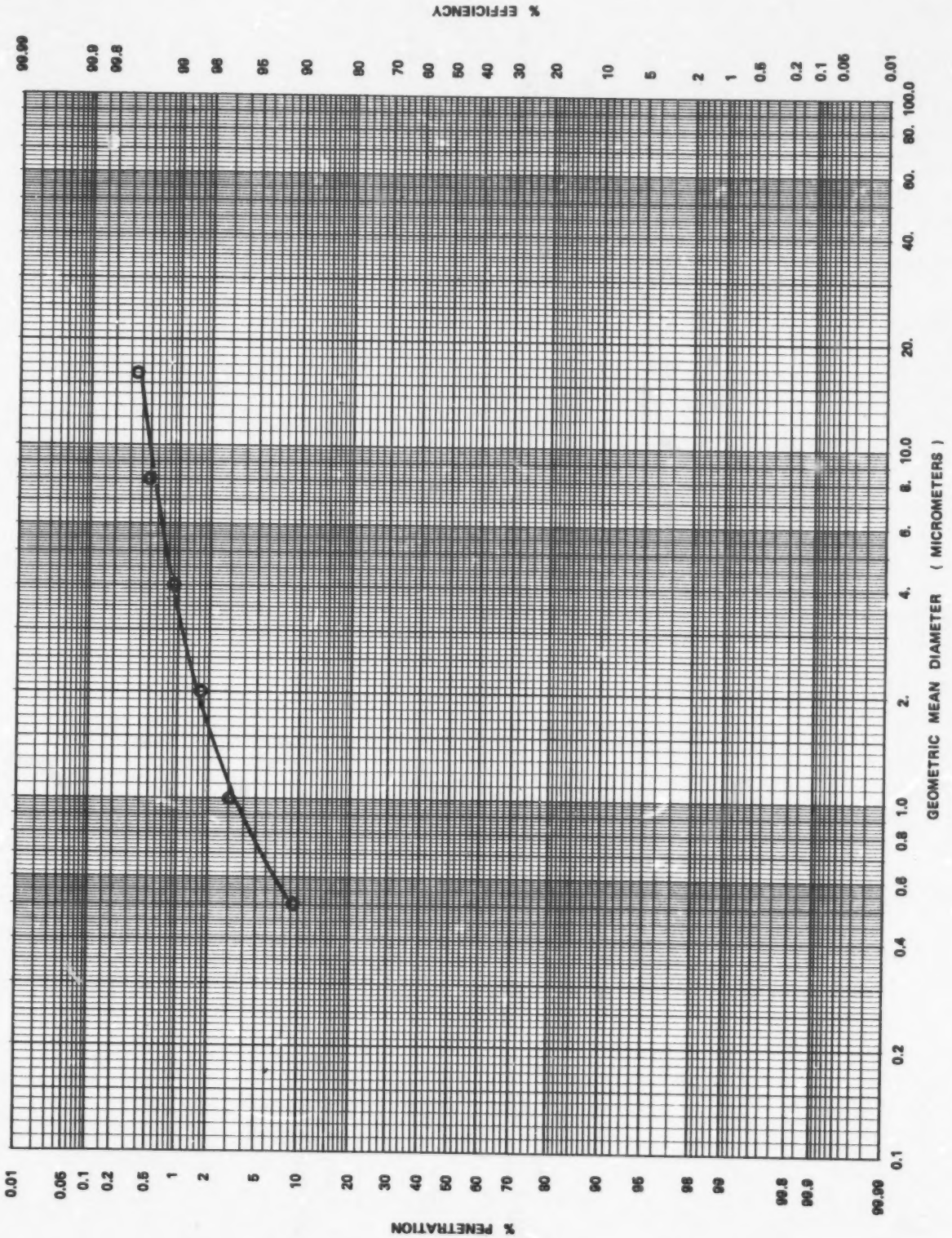

Figure 7. Fractional Efficiency for May 19, 1976
(Based on single outlet sampling point)

Table 1. Mass Train Results Reported by Research Cottrell

Date	Boiler Load MW	Temperature, °C (°F) In	Temperature, °C (°F) Out	Gas Volume, m^3/sec (ACFM) In	Gas Volume, m^3/sec (ACFM) Out	Dust Concentration gm/m^3 (gr/ACF) In	Dust Concentration gm/m^3 (gr/ACF) Out	Efficiency %	Specific Collecting[1] Area $m^2/(m^3/sec)$ (ft^2/1000 ACFM)
3-27	299	107 (224)	96 (204)	417 (833,000)	585 (1,240,000)	6.32 (2.76)	0.482 (0.21)	92.4	34.02 (173)
3-28[2]	299	111 (231)	93 (199)	349 (740,000)	386 (819,000)	6.04 (2.64)	0.593 (0.259)	90.2	51.6 (262)

1. Based on outlet flow rates
2. Gas flow appears inconsistent with boiler load.

Date	Test No.	Description
5/19/76	2-1	SO_2 converter temperature fell; SO_3 injection rate uncertain
5/19/76	2-2	Normal test
5/20/76	2-3	Interrupted due to TR set failure
5/21/76	2-4	Interrupted due to TR set failure

Table 2 summarizes the data obtained by Kin Associates on May 19. The dissolved solids in the first impinger were obtained to determine whether any SO_3 remaining in the gas phase at the stack would appear in the residue after evaporation of the liquid. The results in Table 2 indicate that the outlet mass loading is increased about 18% if the impinger solids are included. Chemical analyses of the impinger wash were also conducted, and these results are discussed in a subsequent section.

It is of interest to compare the mass loadings obtained with the mass trains in the stack with that obtained from the single point measurement with the Andersen impactor at the precipitator outlet. The Andersen impactor obtained a mass loading of 0.0227 gm/m^3 (.00992 gr/ACF) which is only 32% of the results indicated by the EPA train without inclusion of the impinger. Thus, the fractional efficiencies plotted in Figure 7 are not representative of the overall precipitator performance. It is probable that most of the relatively large particles resulting from rapping reentrainment are concentrated near the bottom of the duct and were, therefore, not captured by the impactor. The data in Figure 7 should, however, provide a reasonably accurate representation of sub-two micron collection efficiencies. Similarly, the total mass loadings obtained with the limited impactor traverses at the inlet will show significant disagreement with the mass train results, but the smaller size fractions should be represented with sufficient accuracy for use as input data to the precipitator computer model.

A comparison of the ASME-derived mass loadings and precipitator efficiencies in Tables 1 and 2 shows that, for the brief period when

Table 2. Mass Train Results Reported by Kin Associates

Date	Boiler load MW	Temperature, °C (°F) In	Temperature, °C (°F) Out	Gas Volume m^3/sec (ACFM) In	Gas Volume m^3/sec (ACFM) Out	Dust Concentration gm/m^3(gr/ACF) In	Dust Concentration gm/m^3(gr/ACF) Out ASME	Dust Concentration gm/m^3(gr/ACF) Out EPA	Dust Concentration gm/m^3(gr/ACF) Out EPA & First Impinger	Efficiency, % ASME	Efficiency, % EPA w/o Impinger	Specific Collecting Area $m^2/(m^3/sec)$ (ft^2/1000 ACFM)	Test No.
5-19	303	129 (264)	122 (252)	557 (1,180,000)	476 (1,009,000)	6.85 (2.99)	0.0508 (0.0222)	0.0703 (0.0307)	0.0828 (0.0362)	99.27	98.96	41.82 (212)	2-2

normal precipitator operation was possible, the precipitator performance was increased to the extent that outlet mass concentrations decreased by about a factor of ten as a result of the SO_3 injection. This increase in efficiency is consistent with the improvement in power supply performance and the decrease in dust resistivity, as discussed below.

C. Resistivity Measurements

In situ resistivity data were obtained with a point-plane probe[1] during both the baseline and SO_3 injection test series. These data are given in Table 3, and it is apparent that dust resistivity during the SO_3 injection tests is about two decades lower than it was during the baseline series. The data in Table 3 are obtained with parallel plate cell geometry with an applied electric field slightly lower than the value which is sufficient to cause spark-over. It is also possible to obtain resistivity data from the voltage-current characteristics of the apparatus with and without dust on the collecting electrode as illustrated in Figure 8. The collecting area of the measurement cell is 5 cm^2, and resistivity may be calculated from the dust layer thickness 0.09 cm, the voltage difference between the "clean" and "dirty" voltage-current curves (5600 volts), a selected current (0.5×10^{-6}A), and the cell area. Thus,

$$\rho = \frac{(5600V)(5cm^2)}{(0.5 \times 10^{-6}A)0.09\ cm} = 6.2 \times 10^{11}\ \text{ohm-cm}$$

at an applied field strength of 62.2 kV/cm with a current density of 100 nA/cm^2. In contrast, the parallel plate data were obtained with an applied field of 16.6 kV/cm at a current density of 2 nA/cm^2 and the resistivity obtained under these conditions was 8.3×10^{12} ohm-cm. The resistivity value derived from the voltage-current curves is expected to be lower than the parallel plate data under these conditions as a result of electrical breakdown (back corona) in the deposited dust layer.

Table 3. *In situ* Resistivity from George Neal Plant, Unit 2

Baseline Test Series (3/27/76)		SO_3 Injection Test Series		
Temperature °C(°F)	Resistivity ohm-cm	Temperature °C(°F)	Date	Resistivity, ohm-cm
110(230)	8.3×10^{12}	127(261)	5/17/76	4.4×10^{10}
118(244)	5.7×10^{12}	132(270)	5/19/76	3.1×10^{10}
118(244)	5.9×10^{12}	138(280)	5/19/76	1.0×10^{11}
121(250)	6.8×10^{12}	142(288)	5/19/76	4.1×10^{10}
		143(289)	5/20/76	3.5×10^{10}
		143(289)	5/20/76	4.1×10^{10}

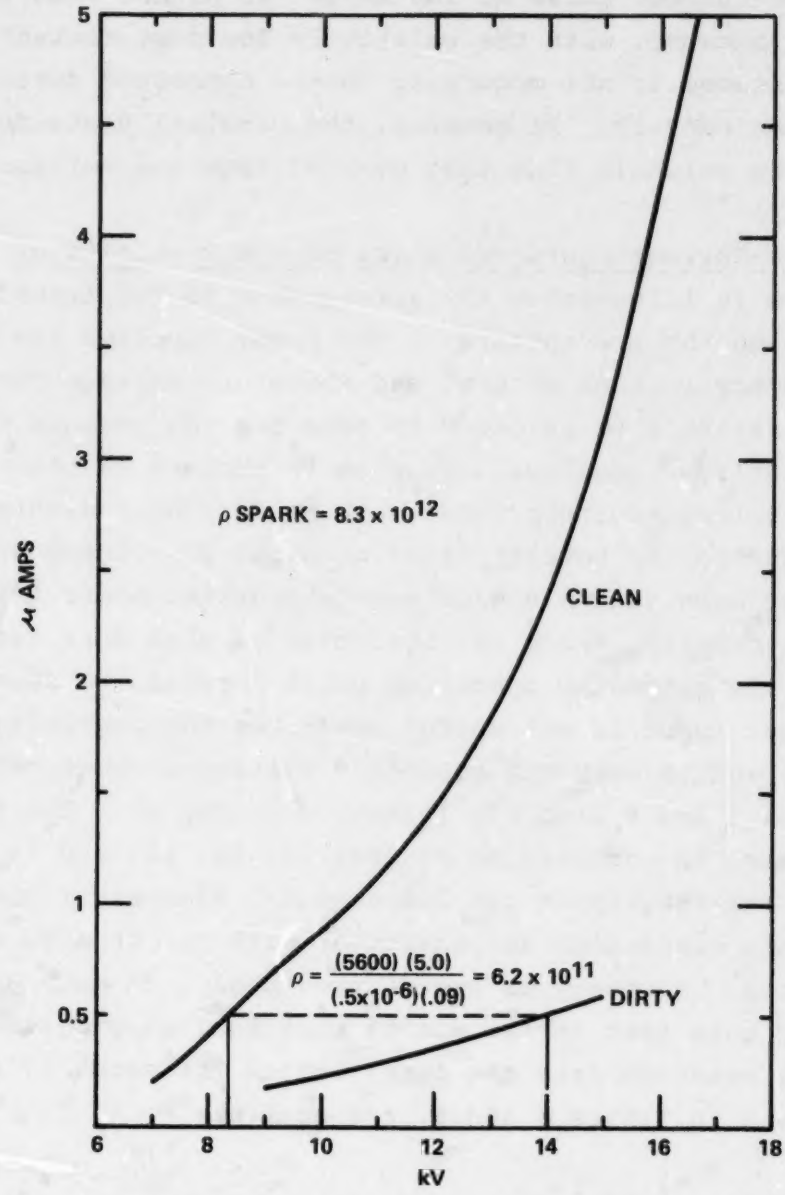

Figure 8. Resistivity Probe Voltage-Current Characteristics without SO_3 Injection

Figure 9 shows the resistivity probe voltage-current relationships with SO_3 injection. Note that the resistivity derived from the voltage-current curve at 100 nA/cm^2 is higher than the parallel plate data because, with the relatively low dust resistivity, electrical breakdown is not occurring in the deposited dust layer at this current density. In general, the parallel plate data are considered more reliable than that derived from the voltage-current curves.

D. Voltage-Current Characteristics of the Precipitator

Figure 10 illustrates the arrangement of the transformer-rectifier sets on the precipitator. The power supplies are not equipped with secondary voltage meters, and therefore voltage divider resistors were attached to selected TR sets for the purpose of obtaining secondary voltage readings. Figures 11 through 14 present the secondary voltage-current relationships for the indicated TR sets obtained during the baseline test on March 27. These curves indicate that back corona and/or severe sparking occur at low values of current density, which is indicative of high dust resistivity. Note that the automatic operating point location is such that much of the power input is not useful power for the precipitation process. Figures 15 and 16 show the secondary voltage-current relationships for TR sets 3 and 8 with SO_3 injection on May 21. The shape of these curves, in contrast to Figures 11, 12, 13, and 14, indicates that dust resistivity is not limiting the electrical operating conditions. This conclusion is consistent with the in situ resistivity measurements. However, as stated previously, TR sets were tripping our during this test series due to dust removal problems. Average electrical readings from the panel meters for March 27 and for May 19 are given in Tables 4 and 5, respectively.

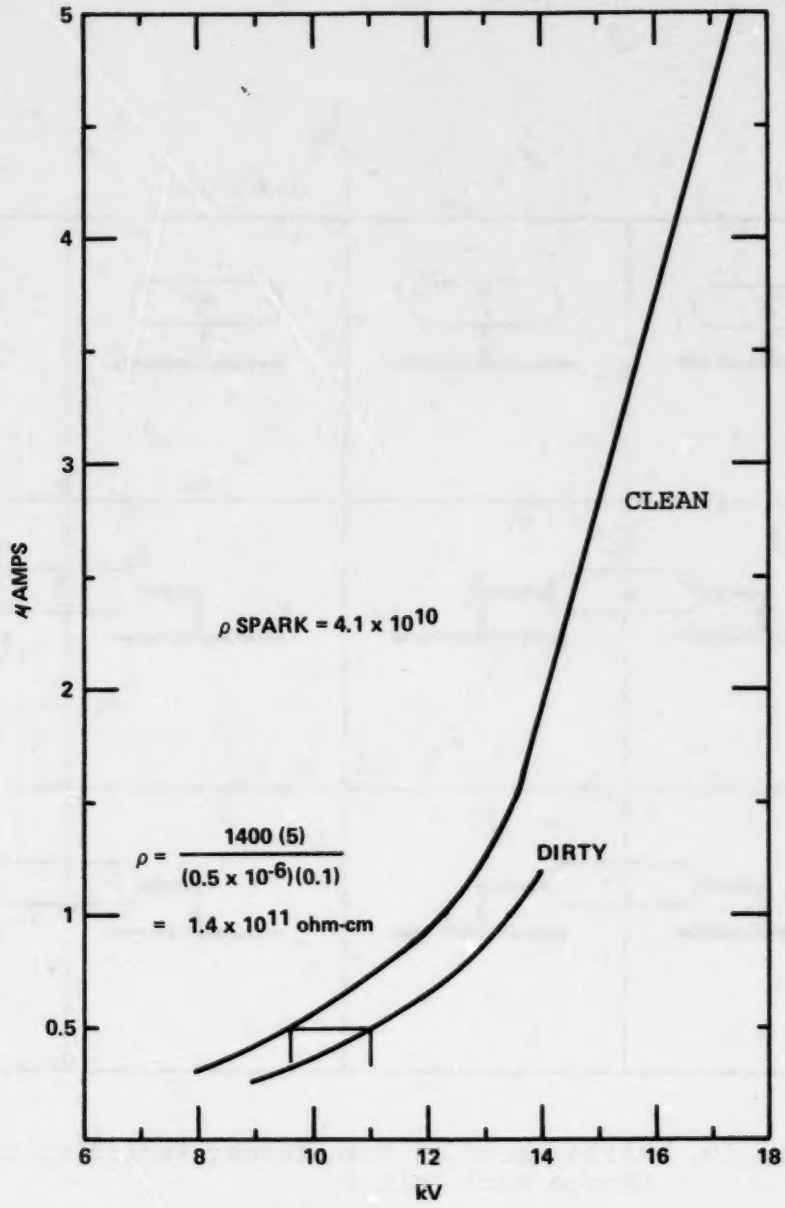

Figure 9. Resistivity Probe Voltage-Current Characteristics with SO_3 Injection

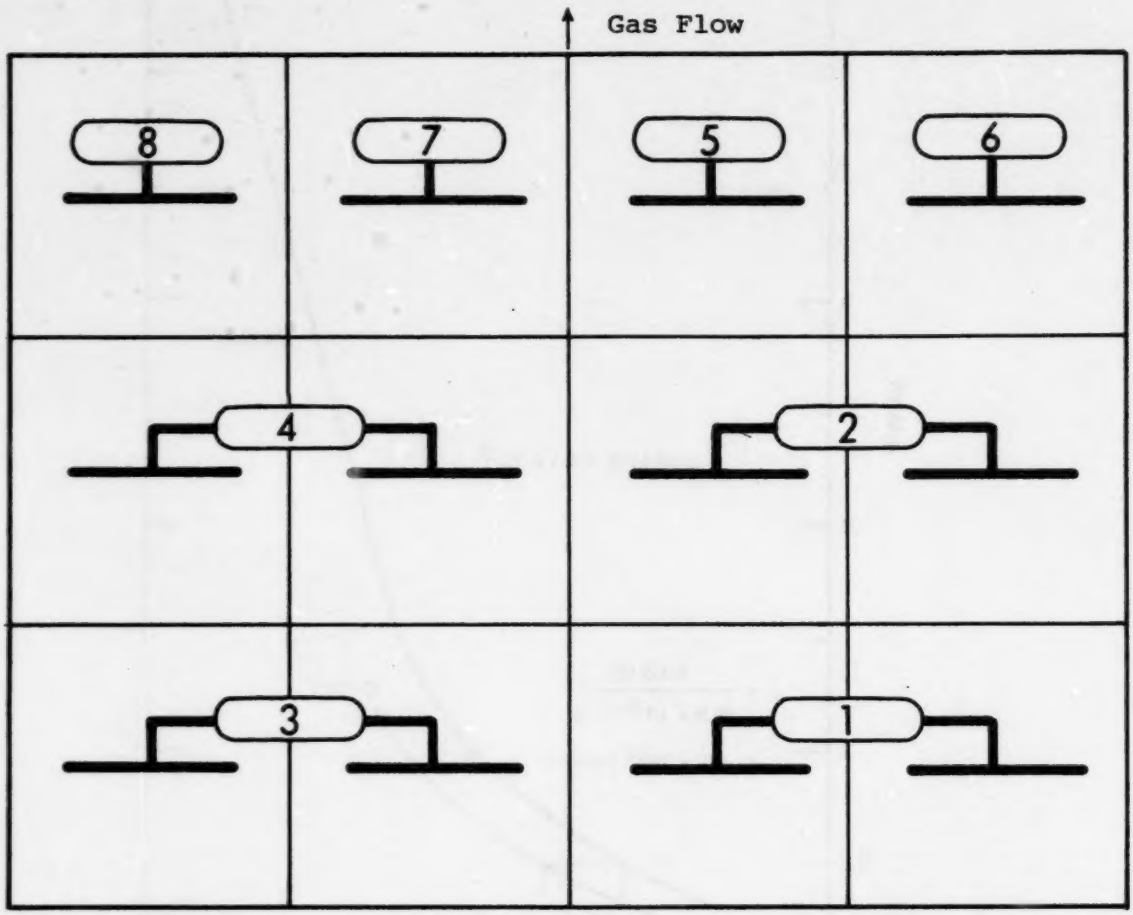

Figure 10. Arrangement of Transformer Rectifier Sets for George Neal Unit 2

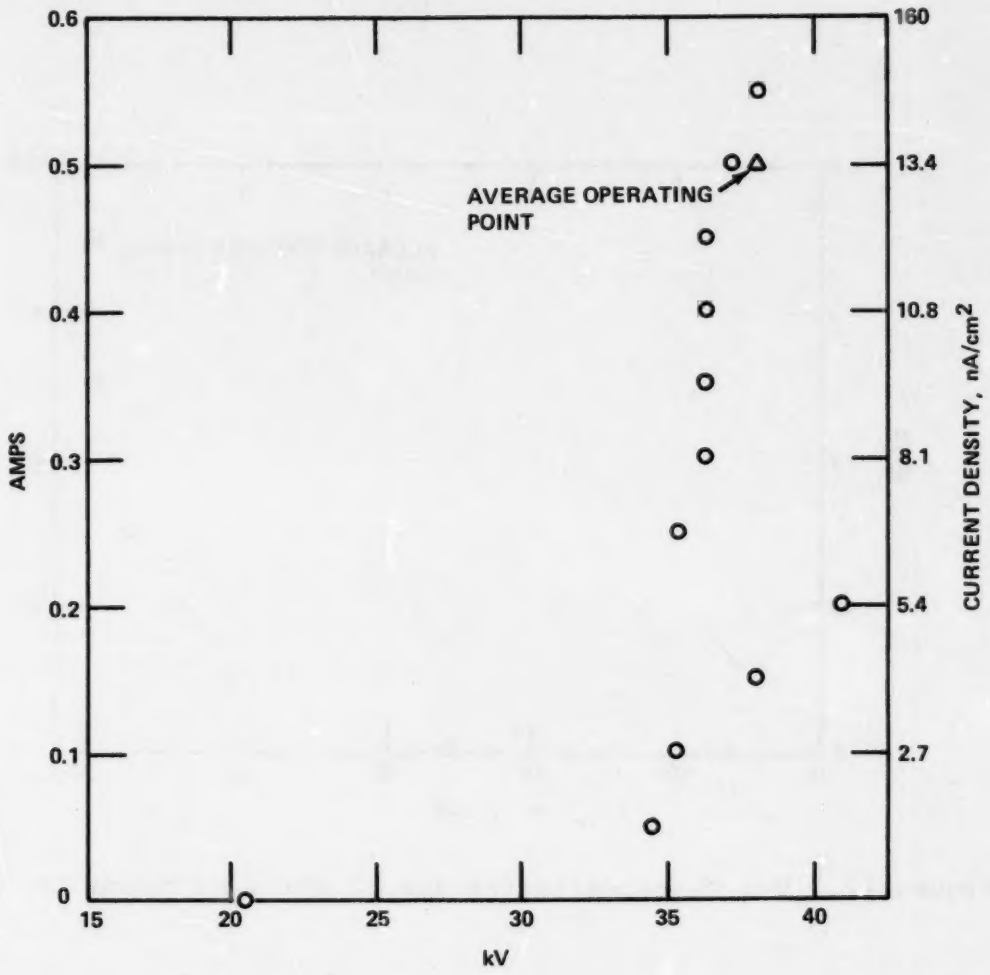

Figure 11. V-I Characteristics for TR Set 3 on March 27, 1976

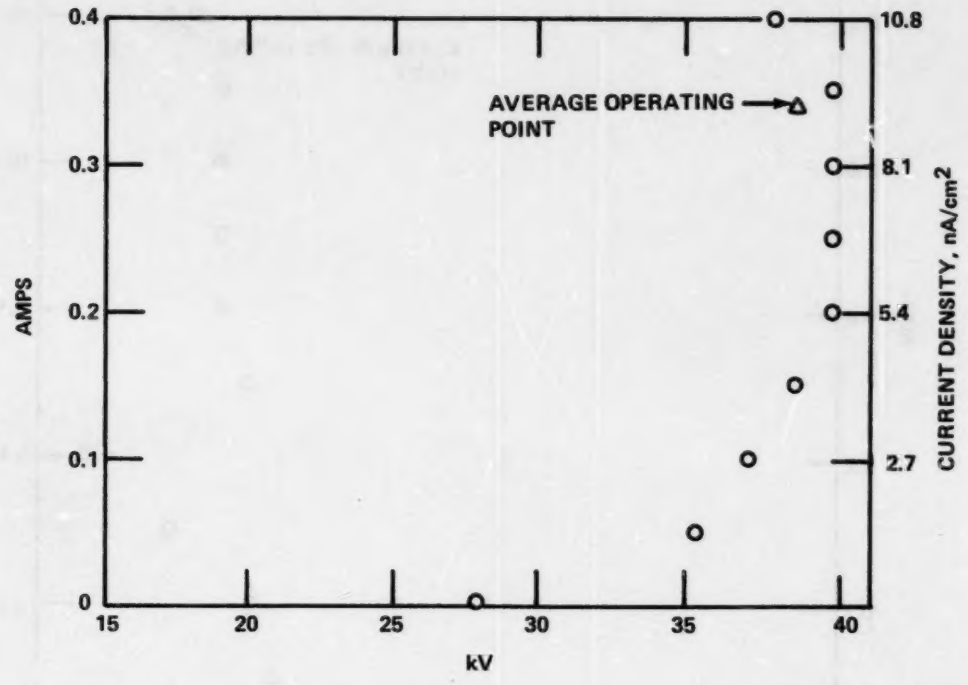

Figure 12. V-I Characteristics for TR Set 4 on March 27, 1976

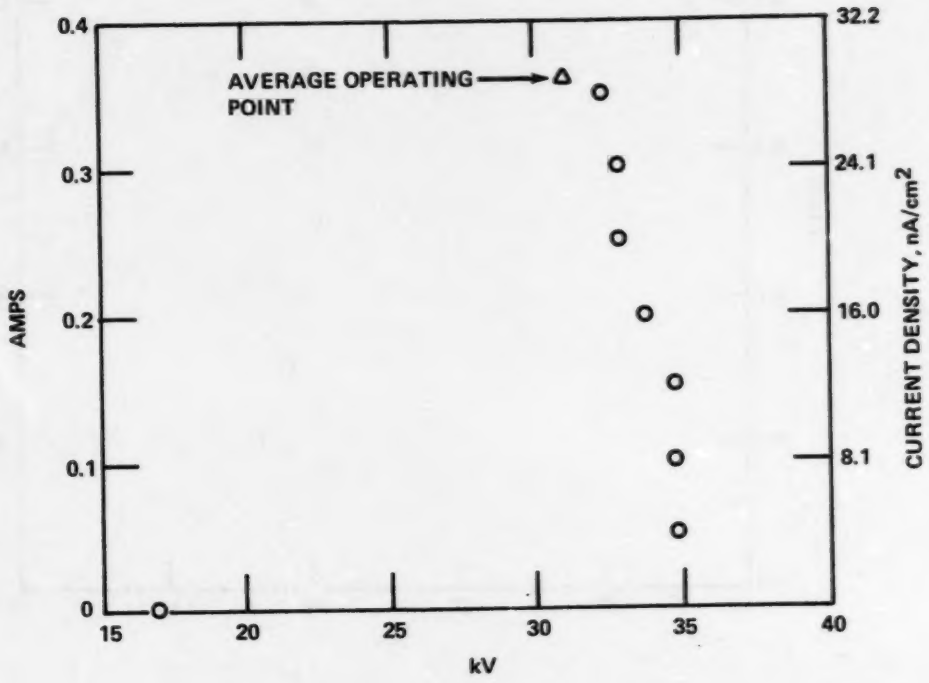

Figure 13. V-I Characteristics for TR Set 7 on March 27, 1976

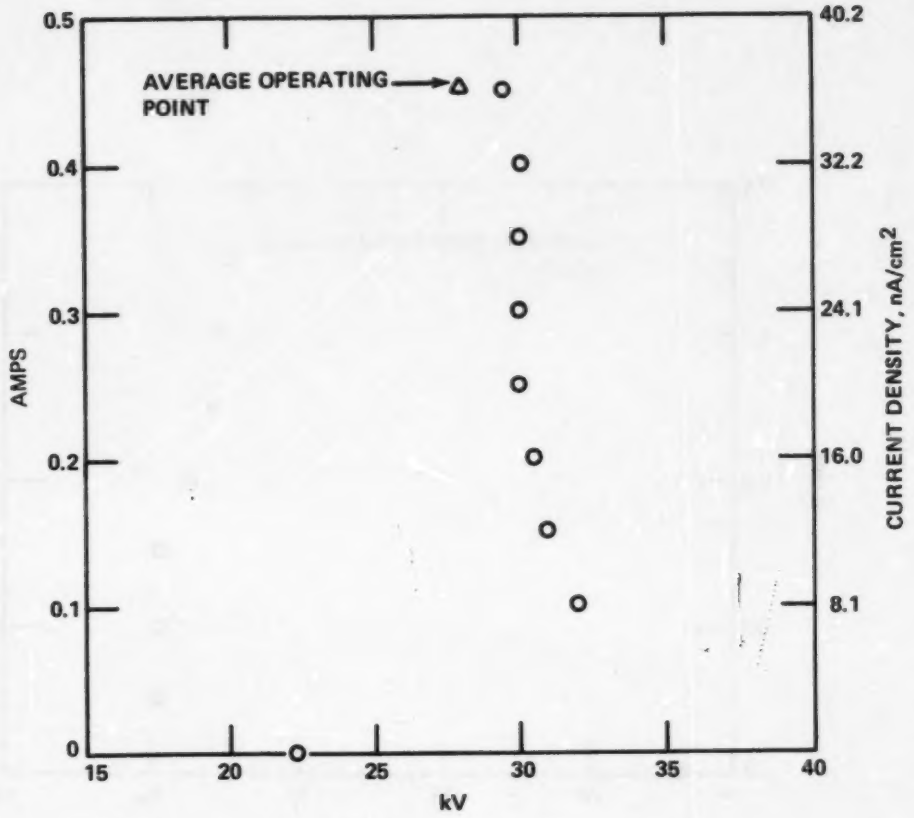

Figure 14. V-I Characteristics for TR Set 8 on March 27, 1976

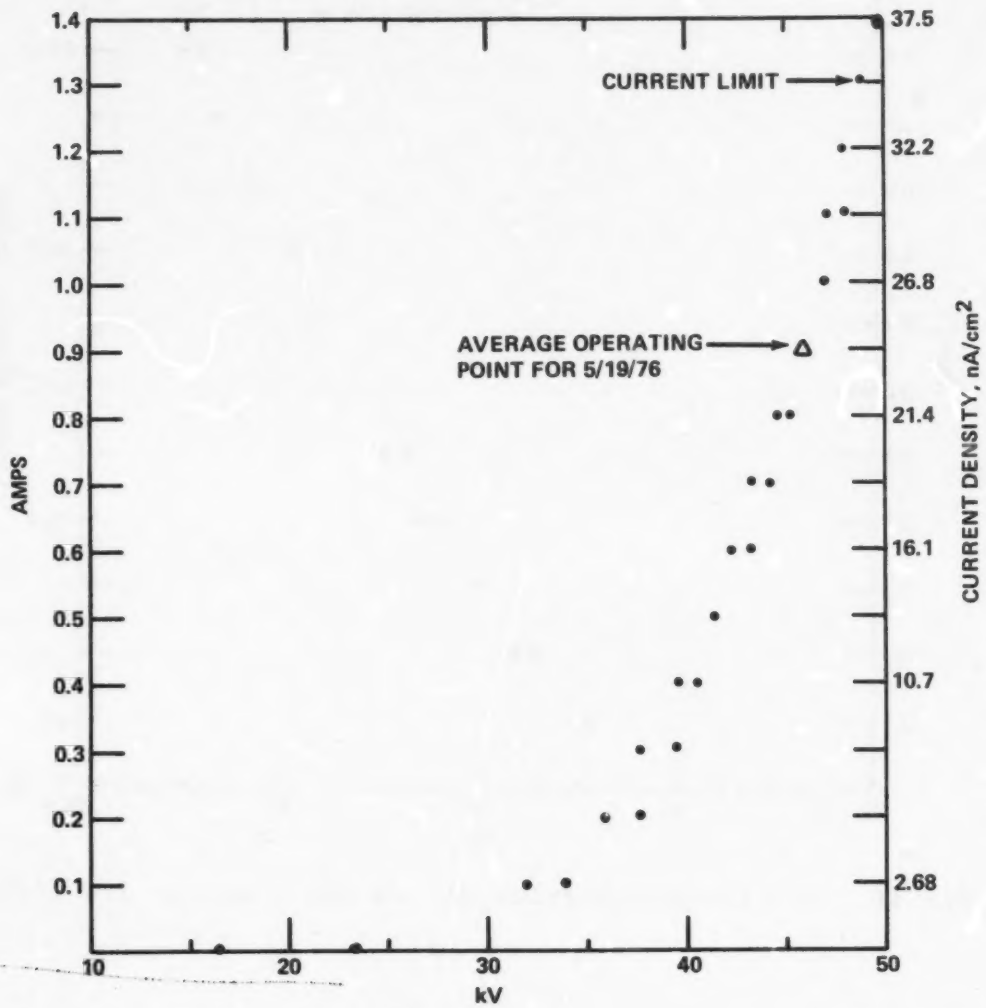

Figure 15. V-I Characteristics for TR Set 3 on May 21, 1976

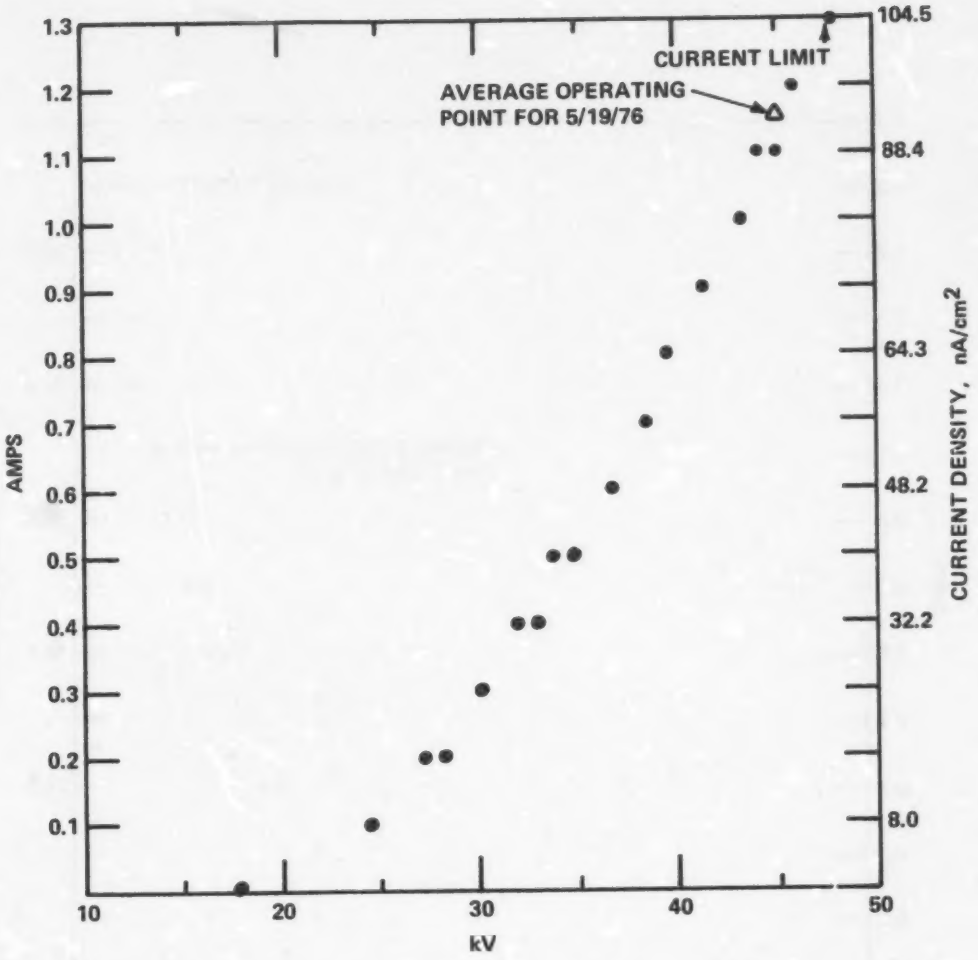

Figure 16. V-I Characteristics for TR Set 8 on May 21, 1976

Table 4. George Neal - Unit 2
Average voltages and currents for 3/27/76

TR#[1]	Primary amps	Primary volts	Secondary amps	Current Density nA/cm^2
7	76	213	0.36	29.0
8	93	230	0.45	36.2
4	80	205	0.34	9.2
3	105	220	0.5	13.4
1	40	170	0.07	1.8
2	30 to 40	150 to 200	0.06 to 0.14	(sparking, meters swinging)
5	140	280	0.8	64.3
6	145	275	0.82	65.9 no sparking
6[2]	110	225	0.43	34.6 sparking

1. TRs 1, 2, 3, and 4 each have 40,176 ft^2 collecting surface. TRs 5, 6, 7, and 8 each have 13, 392 ft^2 collecting surface, for 214,272 ft^2 total.

2. Average readings during sparking.

Table 5. Average voltages and currents for 5/17/76

TR No.	Primary Amps	Primary volts	Secondary amps	Current Density nA/cm^2
7[1]	86.1	215	.474	38.1
8	191	346	1.156	92.9
4	199	295	1.137	30.5
3	164	328	.917	24.6
1	137	306	.728	19.5
2	220	312	1.397	37.4
5	195	353	1.234	99.2
6	193	349	1.248	100.0

1. Declined from 1.18 amps to 0.15 amps at end of day.

E. Chemical Analyses

1. Coal

Ultimate analyses of four coal samples (one collected during the baseline test and three during the conditioning tests) are given for the "as received" condition in Table 6. The data show a reasonable degree of uniformity, as desired. The aspect of the coal composition that is of primary interest is the sulfur concentration, which is around 0.6% by weight.

2. Flue gases

The vapors of SO_2 and H_2SO_4 were determined with a sampling train in which the H_2SO_4 was first condensed around 70°C (160°F) and the SO_2 was absorbed in a bubbler filled with aqueous H_2O_2. Each sample was titrated as dilute H_2SO_4 with $Ba(ClO_4)_2$ and Thorin as the endpoint indicator.[2] The concentration of H_2O vapor was determined by condensing part as the liquid and absorbing the remainder with silica gel. Concentrations of CO_2 and O_2 were determined by Orsat analysis.

Theoretical concentrations of CO_2, H_2O, O_2, and SO_2 were computed by using the coal analysis in Table 6 and assuming the combustion air contained 2% of H_2O vapor. The percentage of excess air was not known; hence, predicted concentrations of the flue gases were displayed in a graph as functions of excess air to permit a comparison with the experimental results.

Table 7 gives the results of the experimental determinations, and Figure 17 compares these results (except for H_2SO_4) with the computed curves for varying percentages of excess air. The data in the table indicate that during the conditioning tests the concentrations averaged 11.9% CO_2, 7.2% H_2O, 5.6% O_2, and 431 ppm SO_2. No reliable data were obtained for the first three of these gases during the baseline test; however, the somewhat higher result for SO_2 during the baseline test indicates that a lower excess air level was used during this test. The data for H_2SO_4 were higher

Table 6. Ultimate Analyses of Coal Samples

	Baseline Test	Conditioning Tests			
	3/27	5/19N	5/19PM	5/21N	Average
Moisture[1]	6.86	6.28	5.91	5.89	6.03
Carbon	60.83	62.24	59.72	60.89	60.96
Hydrogen[2]	4.88	5.56	4.60	4.37	4.84
Nitrogen	1.26	0.65	0.88	1.26	0.93
Sulfur	0.66	0.57	0.61	0.57	0.57
Ash	10.45	10.66	13.84	11.52	12.00
Oxygen[2]	15.06	14.05	14.44	15.50	14.67
Btu/lb	10,949	11,047	10,579	11,008	10,878

[1]Determined by air drying.

[2]Elements assumed to be present as chemically-bound water (all of the oxygen and an equivalent amount of the hydrogen - less than the total of hydrogen, of course).

Table 7. Analyses of Flue Gas

	Baseline Test	Conditioning Tests					
Sampling Conditions							
Date	3/27	5/19	5/19	5/20	5/20	5/21	5/21
Location	Inlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
Temperature, °F	250	265	250	285	250	285	250
°C	121	129	121	141	121	141	121
Flue-gas Concentration							
CO_2, %	---	11.7	11.6	11.2	11.0	12.9	12.9
O_2, %	---	6.0	6.0	6.3	6.2	4.6	4.5
H_2O, %	---	6.6	7.6	6.7	8.1	7.1	7.3
SO_2, ppm	521	473	419	446	391	428	----
H_2SO_4, ppm	0.4	1.2	0.9	10.6	0.6	8.0	----

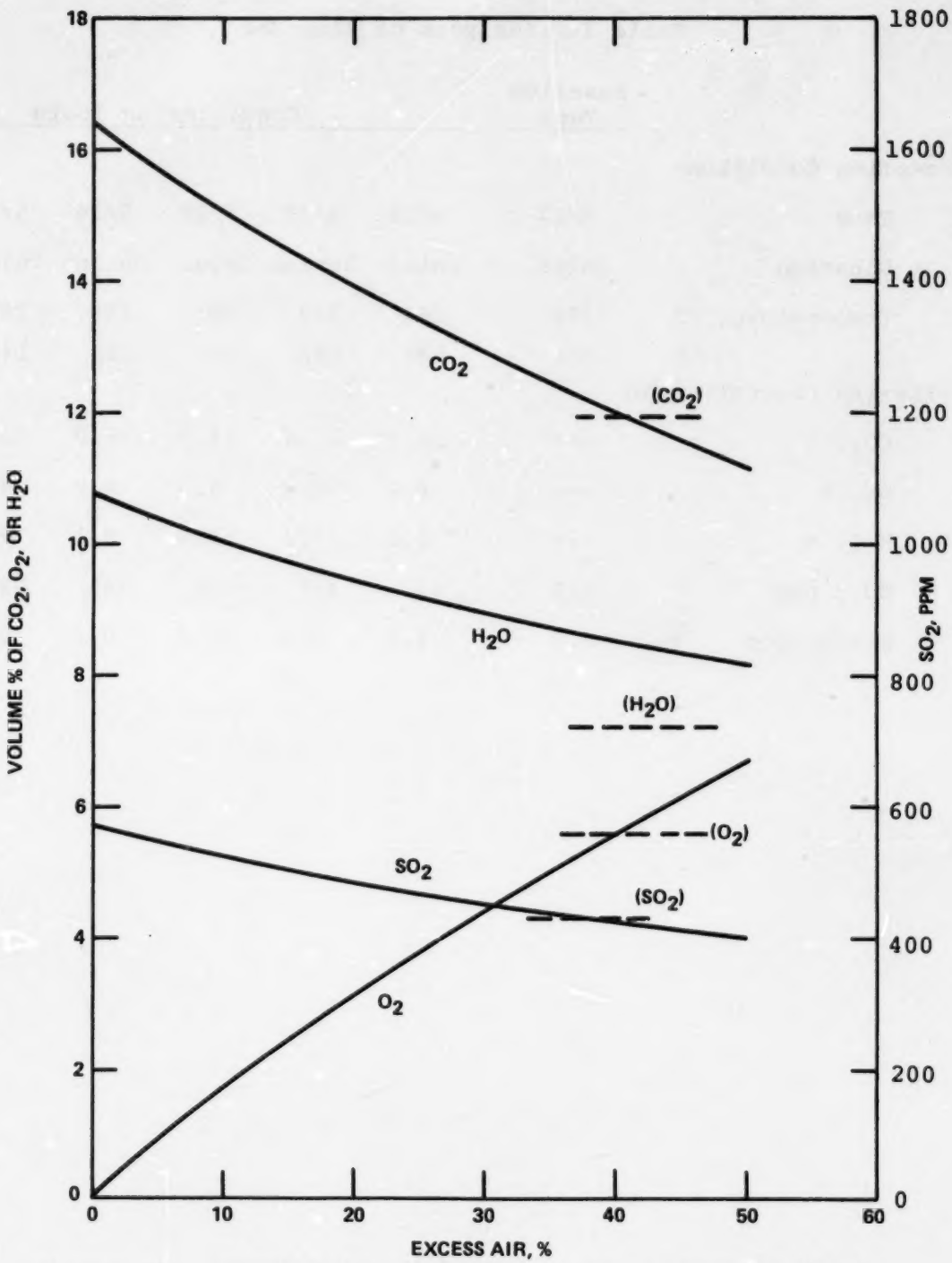

Figure 17. Comparison of Predicted Gas Concentrations (Functions of Excess Air) with Observed Concentrations (Displayed by Dashed Horizontal Lines)

during conditioning as expected; no average of these data is meaningful, however, because of the variation in the sampling temperature (a point later discussed in greater detail).

The comparison of observed and predicted concentrations in Figure 17 shows the experimental results lying on the predicted curves at excess air levels as follows: O_2, 40% excess air; H_2O, >50% excess; CO_2, 42% excess; and SO_2, 38% excess. These comparisons lead to two observations: (1) the experimental concentrations of CO_2, O_2, and SO_2 are consistent with the same excess air level (about 40%) but (2) the concentration of H_2O indicates a considerably higher air level and is thus probably lower than the true value (the estimated true concentration of H_2O is about 8.5%).

3. Fly ash

a. Overall oxide composition

Samples of fly ash were collected from selected hopper locations under the precipitator to be analyzed for overall composition as expressed by oxide concentrations. The configuration of the hopper system is shown in Figure 18. The hoppers used in sampling during the baseline test were Nos. 16 (inlet row) and 8 (outlet row); those used in the conditioning tests were Nos. 17 (inlet) and 9 (outlet). All of the samples were thus taken from hoppers adjacent to the midline of the precipitator.

For each inlet and outlet sample taken at a given time, a composite was prepared to represent the appropriate amounts from each source. The ratio of inlet sample to outlet sample in the composite was 3.6:1.0 for the baseline test or 10.0:1.0 for the conditioning tests.

The appropriate ratios were computed by assuming that for each test mode (with conditioning or without) the effective migration velocity w in the Deutsch equation was constant through the precipitator from inlet to outlet. In view of the fact that the electrode area over the inlet hoppers is one-half of the total, equations involving the total precipitation efficiency E_t and the inlet

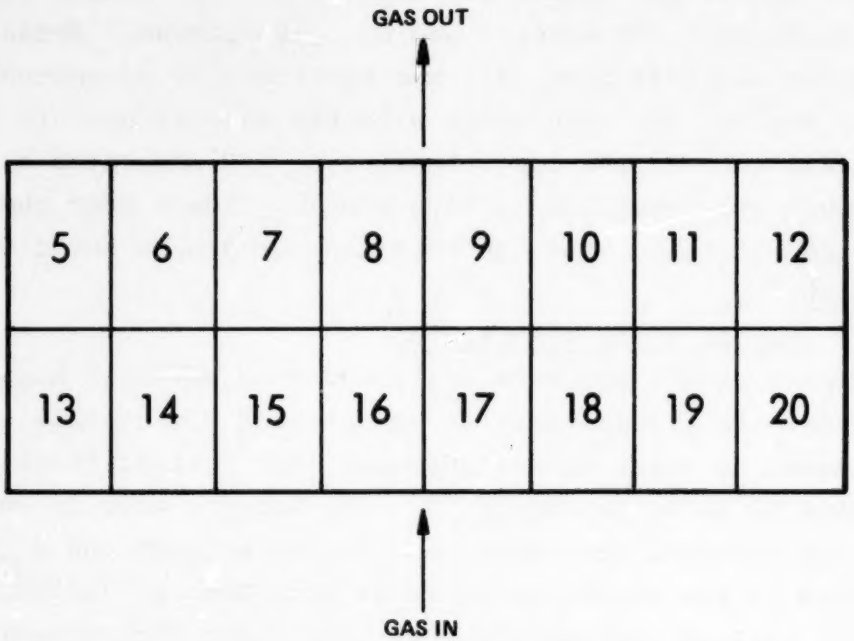

Figure 18. Hopper Configuration for the Precipitator

precipitation efficiency E_i can be written in terms of the respective electrode areas A_t and A_i as follows:

$$\ln(1 - E_t) = -A_t w/V$$
$$\ln(1 - E_i) = -A_i w/V$$
$$= -0.5\ A_t w/V$$
$$= 0.5\ \ln(1 - E_t)$$

Therefore,

$$1 - E_i = (1 - E_t)^{0.5}$$
$$E_i = 1 - (1 - E_t)^{0.5}$$

The fractions of ash received by the inlet and outlet hoppers, respectively, are E_i and $(E_t - E_i)$. Hence, the ratio of masses is given by

$$\frac{\text{Inlet mass}}{\text{Outlet mass}} = \frac{E_i}{E_t - E_i} = \frac{1 - (1 - E_t)^{0.5}}{E_t - 1 + (1 - E_t)^{0.5}}$$

With E_t taken as 0.924 for the baseline test, the computed mass ratio is 3.6. Similarly, with E_t taken as 0.990 for the conditioning tests, the result is 10.0.

A portion of each composite sample was ignited to determine the weight loss during ignition and then it was divided into three final fractions that were separately dissolved in (a) a mixture of HF and H_2SO_4, (b) fused NaOH, and (c) fused Na_2CO_3. The fraction dissolved by acid was analyzed for Li, Na, K, Mg, Ca, Fe, and Ti by atomic absorption spectroscopy and for P by a colorimetric procedure. The fraction dissolved in fused NaOH was analyzed colorimetrically for Al and Si, and the fraction dissolved in fused carbonate was used for turbidimetric determination of S as SO_3.

The results of the analyses expressed as oxide weight percentages are given in Table 8. These data indicate that the major difference (on a relative basis) in the samples from the baseline and conditioning tests was in % SO_3; the difference was a gain of about 0.67% as the result of SO_3 injection during the conditioning tests.

Table 8. Analyses of Hopper Ash

Component	Weight %, Baseline Test				Weight %, Conditioning Tests				
	3/27AM	3/27AM	3/27PM	Avg.	5/19AM	5/19PM	5/20	5/20	Avg.
Li_2O	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Na_2O	0.39	0.34	0.34	0.36	0.45	0.45	0.39	0.46	0.44
K_2O	1.9	1.9	2.0	1.9	1.9	2.0	1.8	1.7	1.9
MgO	2.6	3.0	2.3	2.7	2.9	2.9	2.4	3.0	2.8
CaO	13.6	15.0	14.4	14.3	15.0	13.1	13.2	14.6	14.0
Fe_2O_3	6.7	6.5	6.4	6.5	5.7	5.9	5.9	6.0	5.9
Al_2O_3	17.9	19.6	19.5	19.0	17.9	17.9	17.2	18.3	17.8
SiO_2	53.0	48.7	51.9	51.1	50.3	51.7	53.0	53.4	52.1
TiO_2	1.3	1.0	0.9	1.1	0.9	0.9	0.8	1.1	0.9
P_2O_5	0.2	1.1	0.9	0.7	0.7	0.7	0.6	0.7	0.7
SO_3	0.78	0.75	0.75	0.76	1.38	1.66	1.26	1.42	1.43
LOI	0.39	0.18	0.21	0.33	0.51	0.58	0.50	0.44	0.51

b. pH and soluble sulfate concentration

Determinations of the pH values of fly-ash slurries in distilled water and the concentrations of SO_4^{-2} dissolved in the slurries were made for ash samples from several sources: (1) precipitator hoppers, (2) cyclones used for sampling from the flue-gas ducts, and (3) filters used for sampling from the stack. For the determination of pH and soluble SO_4^{-2} values, 0.1 g of ash was mixed with 30 ml of distilled water and stirred until the pH reached a stable value. This pH value was then recorded; the liquid phase was separated from the suspended solids and analyzed for SO_4^{-2}.

(1) Hopper samples. The data for hopper samples are given in Table 9. The pH values listed are in the highly alkaline range; all are above pH 11 and show no significant variation with hopper source or with sampling conditions (with or with SO_3 injection). Within the first minute or so after addition of fly ash to water, however, the samples taken during SO_3 injection showed evidence of free H_2SO_4 on the ash surfaces. Minima in the range pH 4-5 occurred with the conditioned samples, but such pronounced minima with unconditioned samples were not usually observed. The eventual rise in pH to values above 11 is attributed to the excess of soluble base toward the interior of the ash particles.

The data for SO_4^{-2} in ash samples taken across the inlet to the precipitator are plotted in Figure 19. Across the bottom of the horizontal axis, hopper numbers are shown to identify the locations within the precipitator where the samples originated; across the top, temperatures measured in the inlet duct upstream from the hoppers are given to show the temperature gradient resulting from the Ljungstrom air preheater. The data for two complete sets of hopper samples taken during SO_3 injection are plotted and connected by line segments; averages of results for individual hopper samples taken with and without injection are also plotted.

Table 9. pH Values and Soluble SO_4^{-2} Concentrations[1] of Hopper Ash

Hopper No.		Baseline Test				Conditioning Tests							
		3/27 AM		3/27 PM		5/19 N		5/19 PM		5/20		5/21	
Inlet	Outlet	pH	SO_4^{-2}	pH	SO_4^{-2}	pH	SO_4^{-2}	pH	SO_4^{-2}	pH	SO_4^{-2}	pH	SO_4^{-2}
13													
	5									11.7	0.7		
14												11.3	2.0
	6									11.5	1.6		
15												11.3	1.6
	7									11.5	1.3		
16		11.6	0.7	11.5	0.3							11.4	1.7
	8	11.7	0.5	11.7	0.5					11.7	0.7		
17						11.6	1.1	11.5	1.2			11.4	1.4
	9					11.6	1.3	11.5	1.3	11.7	0.4		
18												11.5	1.0
	10									11.6	1.3		
19												11.6	0.7
	11									11.6	1.1		
20												11.6	0.7
	12									11.6	0.7		
												11.6	0.7

[1]Weight percentage

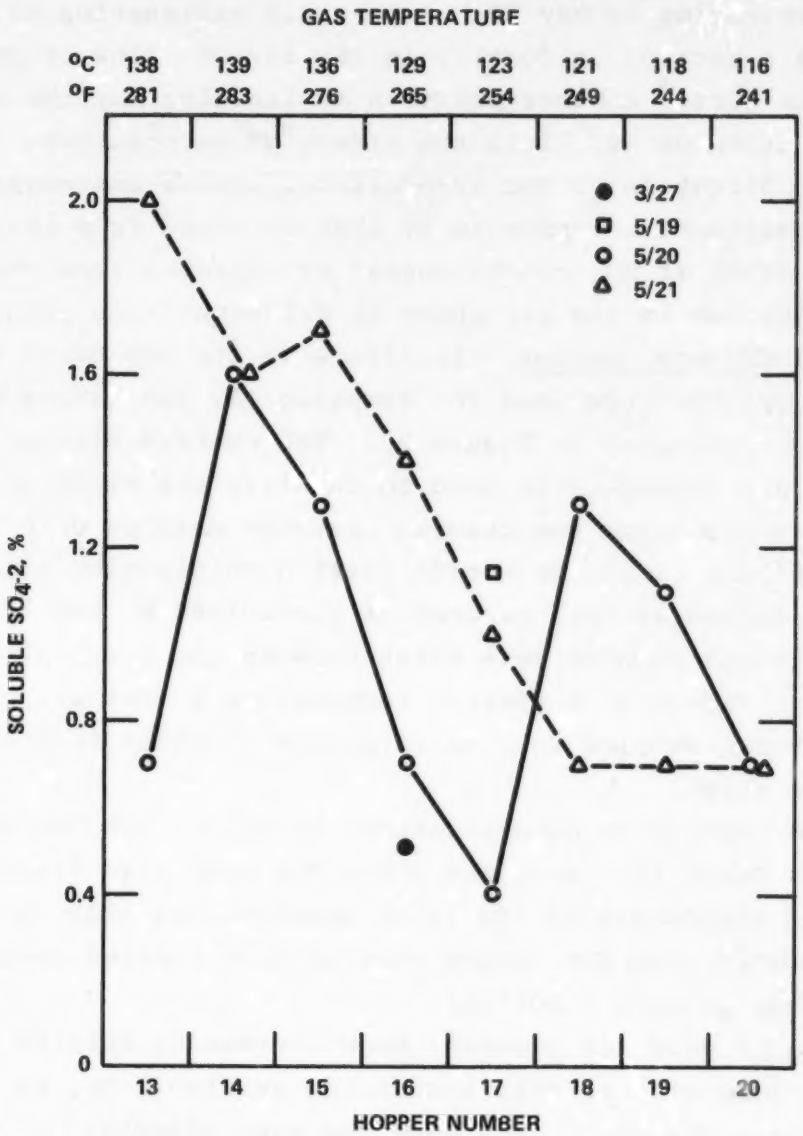

Figure 19. Soluble SO_4^{-2} in Hopper Ash as a Function of Hopper Location or Gas Temperature

The variation in SO_4^{-2} across the precipitator inlet shows an essentially continuous, downward trend with decreasing gas temperature during SO_3 injection on May 21, but show no consistent trend during injection on May 20. A possible explanation of either variation is a lack of uniformity in the rate of flow of SO_3 into the inlet gas duct. Another possible explanation for the more or less regular trend on May 21 is the effect of temperature. However, the observed direction of the trend (simultaneous decreases in both SO_4^{-2} and temperature) is opposite to that expected from previous data in another study of SO_3 conditioning[3] or expected from the observed H_2SO_4 concentrations in the gas phase at different temperatures (Table 7).

(2) Cyclone samples. Locations in the gas ducts where the series cyclones were used for sampling fly ash during conditioning tests are indicated in Figure 20. The numbers circled in this diagram are subsequently used to identify the different samples. It may be seen from the diagram that two samples were taken upstream from the line of SO_3 injection nozzles on opposite sides of the duct at estimated temperatures of 138°C (280°F) and 115°C (240°F), another three samples were taken between the nozzles and the precipitator (again at different temperature extremes), and a final set of three samples were taken at one location in the outlet duct near the stack.

The results of determinations of pH and soluble SO_4^{-2} are given in Table 10. Data are given for each size fraction and for weighted composites of the inlet samples, but only for composites of the outlet samples (which were of such limited quantity to prevent study of each fraction).

The pH data, in general, show increasing acidity with decreasing particle size or with increasing available SO_3 as the result of injection. The SO_4^{-2} data show the same effects.

The only location in the flue-gas train where cyclone samples were collected during the baseline test was at the outlet of the precipitator. A composite of different size ranges of this sample gave these results: pH = 10.8; % SO_4^{-2} = 2.6.

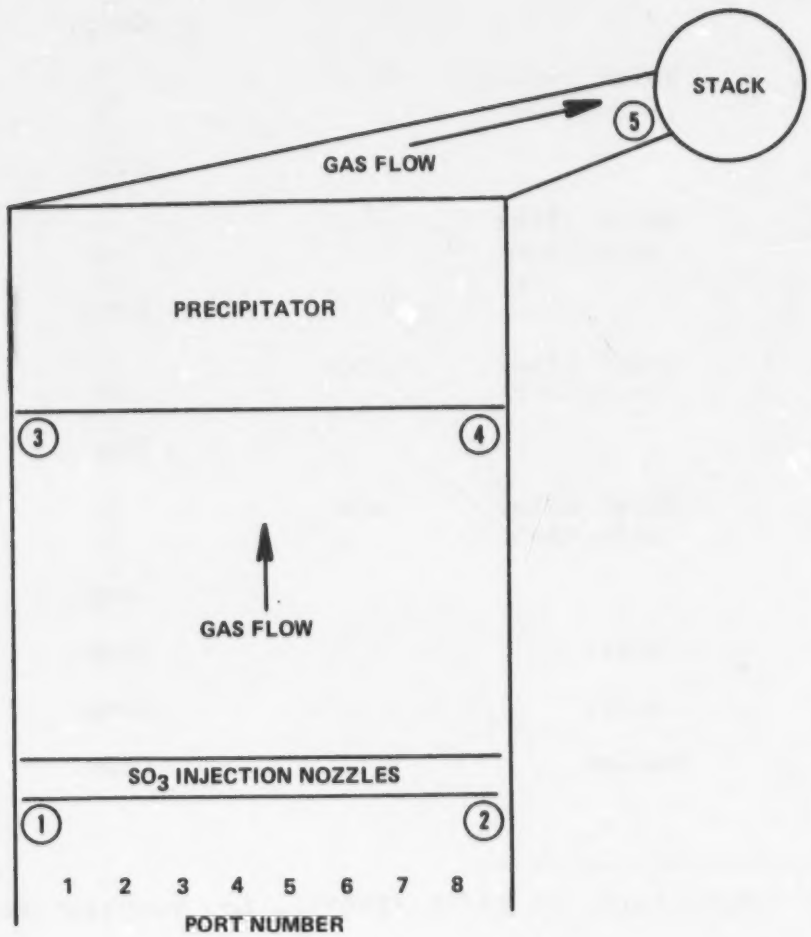

Figure 20. Locations for Sampling with Series Cyclones

Table 10. pH Values and Soluble Sulfate Concentrations of Cyclone Samples of Ash

Sample	Source	Relative Temperature[1]	Size Fraction[2], μm	pH	Soluble SO_4^{-2}, %
1	Inlet before injection	High	C	11.2	0.27
			M	9.8	0.92
			F	8.7	1.5
			Comp.		0.30
2	Inlet before injection	Low	C	11.2	0.34
			M	9.6	0.84
			F	8.7	1.6
			Comp.		0.37
3a	Inlet after injection	High	C	11.1	1.2
			M	11.1	2.0
			F	10.9	3.7
			Comp.		1.6
3b	Inlet after injection	High	C	11.3	0.82
			M	9.5	3.4
			F	6.7	6.6
			Comp.		1.1
4	Inlet after injection	Low	C	11.1	1.2
			M	11.2	1.4
			F	10.8	2.8
			Comp.		1.4
5a	Outlet		Comp.	7.8	6.4
5b	Outlet		Comp.	8.2	6.3
5c	Outlet		Comp.	8.7	7.6

[1] High temperature, ca 138°C (280°F), Low Temperature, ca 115°C (240°F).

[2] C, M, and F correspond to D_{50} values of 2.2, 0.8, and 0.5 μm, respectively. Comp. indicates a composite of all size ranges.

(3) Filter samples. Samples of the fly ash collected on the filters that were used at the precipitator outlet (in the stack) during the efficiency tests were analyzed. These samples were from both the ASME and EPA sampling trains. The results are given in Table 11.

4. Gases absorbed in the EPA mass-sampling train

Analyses were conducted to determine whether nonvolatile material was collected in the impingers of the EPA mass-sampling train at the outlet of the precipitator. Weights of solid material in the first impinger catches were taken into account in calculating the mass concentrations. These weights were determined by drying aliquots of the material caught by use of a temperature high enough to evaporate water rapidly. However, a less vigorous drying procedure could leave a residue of absorbed gases—specifically including H_2SO_4 absorbed from the filtered flue gas or H_2SO_4 produced by absorption of SO_2 from the flue gas and oxidation of the SO_2 in the absorption medium.

In view of this possibility, we performed analyses for absorbed gases in aliquots of the first impinger catches and in composites of the second and third impinger catches. One analytical method employed with a few samples was to titrate absorbed acid with NaOH; the results indicate that comparable amounts of two acids were present: H_2SO_4 and H_2SO_3 (sulfurous acid, or absorbed but unoxidized SO_2). Reasoning that the H_2SO_3 would be lost during any drying procedure, we then removed the H_2SO_3 and determined the remaining quantity of SO_4^{-2} (not only the H_2SO_4 evidently present but also any SO_4^{-2} leached from solid material).

The results of the SO_4^{-2} determinations indicated that virtually equal quantities appeared in the first impinger catch and in the composite of the second and third impinger catches. The total amount of SO_4^{-2} found was equivalent to about 5 ppm of H_2SO_4 vapor, which could give a particulate concentration of about .02 gm/m^3 (0.01 gr/CF)* as H_2SO_4 mist in the plume. As such, the

* Concentration at 21°C and 1 atm.

Table 11. pH Values and Soluble SO_4^{-2} Concentrations of Filter Samples of Ash

Test	Sampling Train	pH	Soluble SO_4^{-2}, %
2-1	ASME	10.4	5.1
	EPA	10.4	4.9
2-2	ASME	9.9	5.6
	EPA	9.6	3.4
2-3	ASME	10.5	4.2
	EPA	---[1]	---[1]
2-4	ASME	9.5	6.2
	EPA	---[1]	---[1]

[1]Filter sample not available for analyses.

SO_4^{-2} found would be significant. However, the finding of SO_4^{-2} concentrations in the second and third impingers that were nearly equivalent to those in the first impinger suggests that much of the SO_4^{-2} found was from absorbed and oxidized SO_2, and not from H_2SO_4 vapor. As SO_2 in the flue gas, the material found would not be logically included in the particulate emission.

IV. MASS BALANCE CONSIDERATIONS

A. Sulfur Excluding Injected SO_3 (Conditioning Test)

It is possible to use the analytical data given in Section III.E to compare the rate of combustion of sulfur in the coal with the rates of production of sulfur compounds in the flue gas and in the fly ash. We made this comparison by using the data from the conditioning tests with carbon as a basis for comparison. In other words, we assumed that all of the carbon in the coal appeared as CO_2 in the flue gas and then compared the mole ratio to sulfur to carbon in the fuel against the mole ratio in the combination of flue gas and fly ash.

For the fuel, the average weight ratio of sulfur to carbon is 0.57/60.96 (Table 6), which corresponds to a mole ratio of:

$$\frac{0.57/32.07}{60.96/12.01} = 3.5 \times 10^{-3}$$

For the flue gas, the average concentrations of SO_2 and CO_2 are approximately 430 ppm and 12% by volume, respectively (Table 7). The concentration of SO_3 in the gas phase prior to injection of this compound is negligible (less than 1 ppm). However, the concentration of SO_3 in the fly ash is not small enough to be ignored. If the weight percentage of SO_3 in the ash prior to treatment with this gas from the conditioning system is taken as 0.76% (Table 8) and the fly ash concentration entering the precipitator is computed on an absolute basis (that is, for moist flue gas) as 9.00 mg/m^3,* then the SO_3 in the ash corresponds to a gas-phase composition of:

$$\frac{0.0076 \times 9.00\ gm/m^3}{80\ gm/mol} = 0.85 \times 10^{-3}\ mol/m^3$$

This concentration is added to the concentration of SO_2, which is:

$$\frac{430 \times 10^{-6}\ m^3/m^3}{24.1 \times 10^{-3}\ m^3/mol} = 17.8 \times 10^{-3}\ mol/m^3$$

* This concentration represents the average of several inlet determinations, expressed for a temperature of 21°C at a pressure of 1 atm with water vapor present.

The concentration of CO_2 is:

$$\frac{0.12\ m^3/m^3}{24.1 \times 10^{-3}\ m^3/mol} = 5.0\ mol/m^3$$

Thus, the mole ratio of sulfur to carbon in the combination of flue gas and fly ash is given by:

$$\frac{(17.8 + 0.85) \times 10^{-3}}{5.0} = 3.7 \times 10^{-3}$$

Three conclusions are now evident. First, the sulfur/carbon ratio in the combustion products (3.7×10^{-3}) agrees remarkably well with the ratio in the fuel (3.5×10^{-3}). Second, there is evidently little of the sulfur in the fuel that is discharged from the boiler as bottom ash. Third, if it is assumed that all of the sulfur in the fuel is initially oxidized to SO_2 but that subsequent partial oxidation of SO_2 to SO_3 occurs in the flue-gas train as the temperature is lowered, then the conversion factor of SO_2 to SO_3 is best represented by the concentration of SO_3 in the fly ash (not in the flue gas). The computed conversion factor is:

$$\frac{0.85 \times 10^{-3}}{(17.8 + 0.85) \times 10^{-3}} \times 100 = 4.4\%$$

B. Injected SO_3: Quantity Accounted for at the Inlet of the Precipitator

1. SO_3 present as H_2SO_4 vapor in the gas phase

Data on inlet concentrations of H_2SO_4 vapor are necessarily limited to the results that could be obtained at the only two sampling ports available between the injection nozzles and the precipitator. The data (given previously in Table 7) were for different temperatures, around 130°C (265°F) toward one side of the duct and around 143°C (290°F) on the other side. They show higher concentrations of H_2SO_4 at the higher gas temperature, as expected.

To obtain a reasonable approximation of the average H_2SO_4 concentration at the precipitator inlet, the following approach was

taken: First, Figure 21 was prepared to compare the H_2SO_4 concentrations found at different sampling temperatures with the concentrations predicted from the data of Banchero and Verhoff[4] at the dew point (theoretically, the maximum vapor concentrations attainable). As expected, the experimental results are portrayed by a curve falling substantially below the dew point curve. Next, Figure 22 was prepared to show average gas temperatures at different distances across the inlet duct (these temperatures were computed from the data of Kin Associates that were obtained in pitot traverses). Also plotted in Figure 22 were H_2SO_4 concentrations at these temperatures as obtained by interpolation of the previous curve (Figure 21) for the experimental values. Finally, the average H_2SO_4 concentration across the duct was computed from the relationship between apparent experimental concentration and location in the duct.

The value of the average thus obtained is 1.8 ppm. It represents the approximate increase in the H_2SO_4 vapor concentration as the result of SO_3 injection (the concentration during the baseline test has been reported as 0.4 ppm but is not large enough to be clearly distinguished from zero).

2. SO_3 present as SO_4^{-2} in the fly ash

Data based on hopper samples. Average values for the total percentage of SO_3 in fly ash collected in hoppers adjacent to the midline of the precipitator are 0.76% without conditioning and 1.43% with conditioning (Table 8). Using the difference of 0.67% as a measure of the effect of SO_3 injection and taking the value of 9.00 gm/m^3 as representative of the fly-ash concentration at the inlet of the precipitator,* one calculates as follows to obtain the concentration of injected SO_3 thus accounted for:

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* This concentration represents the average of several inlet determinations, expressed for a temperature of 21°C at a pressure of 1 atm with water vapor.

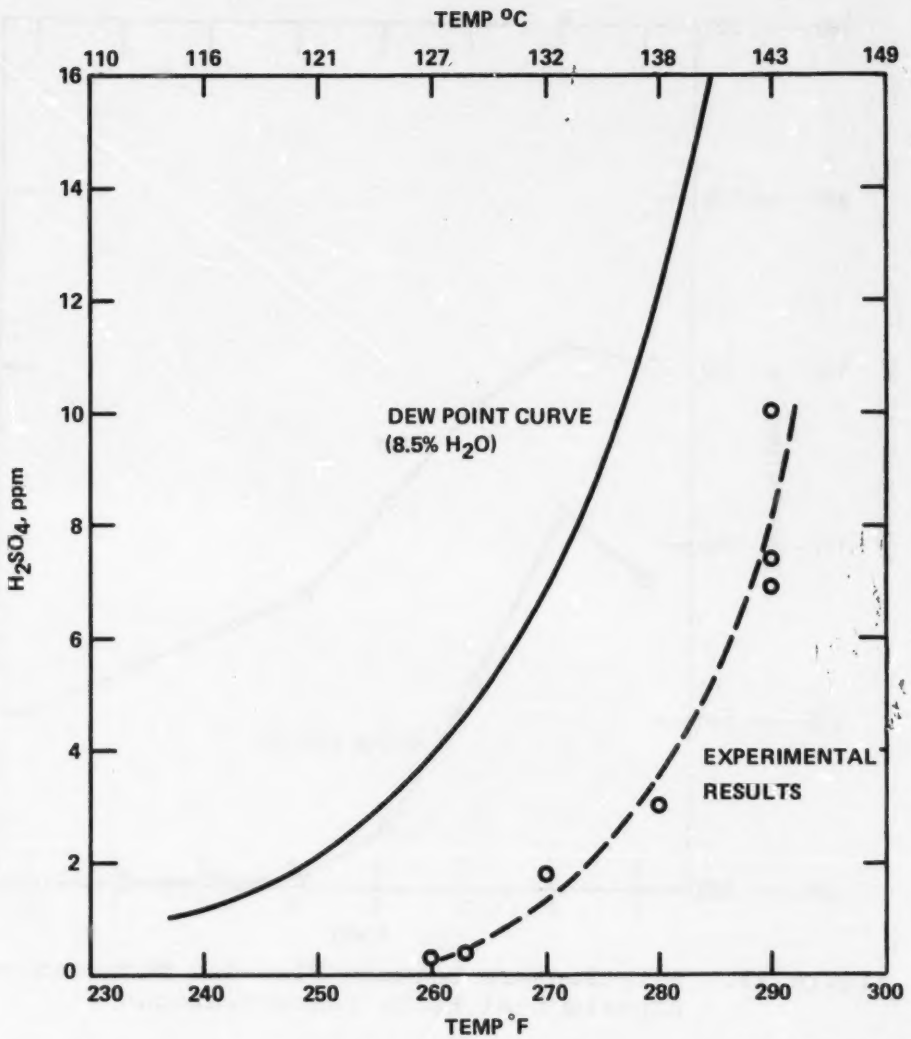

Figure 21. Comparison of H_2SO_4 Concentrations at the Dew Point with Experimental Results

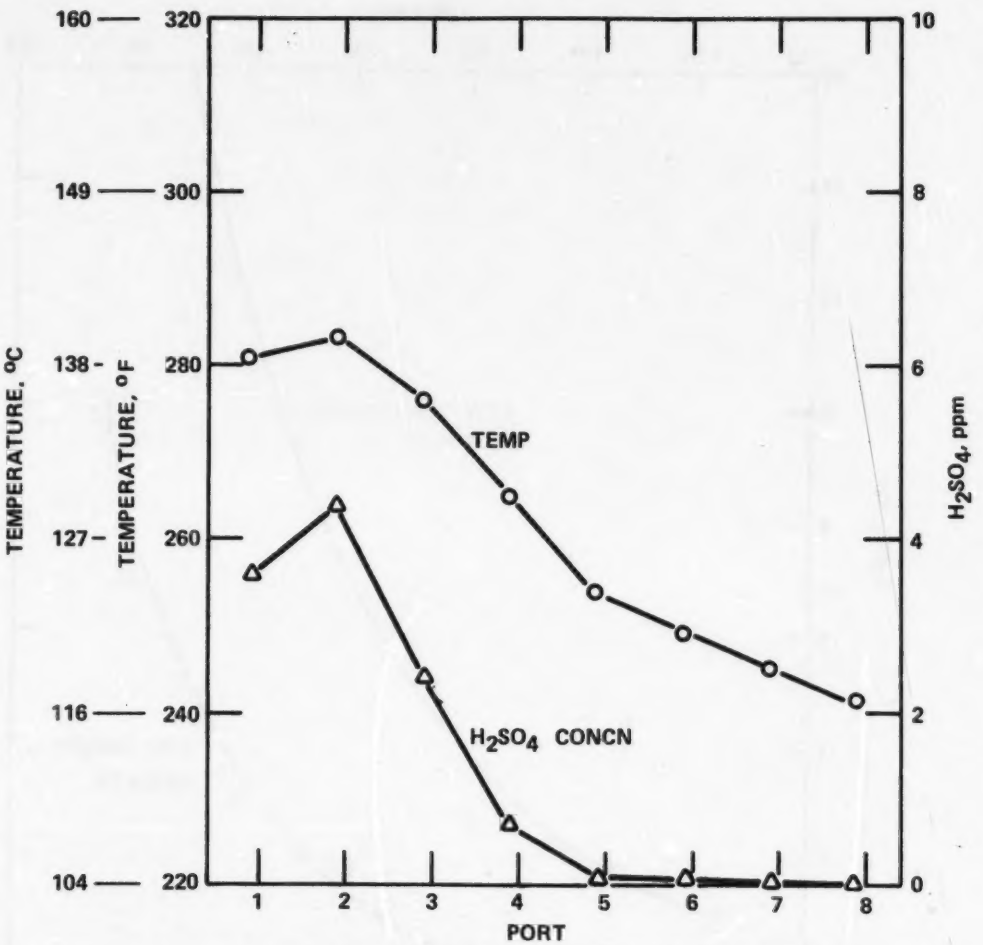

Figure 22. Relationship between Flue-Gas Temperature and Experimental H_2SO_4 Concentrations

$$\frac{0.0067 \times 9.00 \text{ gm/m}^3}{80 \text{ gm/mol}} = 0.75 \times 10^{-3} \text{ mol/m}^3$$

$$0.75 \times 10^{-3} \text{ mol/m}^3 \times 24.1 \times 10^{-3} \text{ m}^3\text{/mol} = 18.0 \times 10^{-6} \text{ m}^3\text{/m}^3$$

In other words, ∿18 ppm or about 75% of the 25 ppm of injected SO_3 is accounted for. In connection with this result, it is necessary to point out that the composition of fly ash collected near the middle of the precipitator may not be representative of the total collected, particularly in view of the erratic nature of results for soluble SO_4^{-2} in ash across the entire inlet of the precipitator (Figure 19).

Data based on cyclone samples. Results of determinations of soluble SO_4^{-2} in fly ash collected in cyclones during SO_3 injection give another basis for calculating the fraction of the conditioning agent found in the fly ash. Two composite samples taken upstream from the injection nozzles were found to contain an average of about 0.34% soluble SO_4^{-2} (Table 10). Corresponding samples taken between the nozzles and the precipitator contained individually 1.6, 1.1, and 1.4% soluble SO_4^{-2} or averaged 1.37%. The difference in the averages, 1.03%, upstream and downstream of the nozzles corresponds to the following concentration of injected SO_3:

$$\frac{0.0103 \times 9.00 \text{ gm/m}^3}{96 \text{ gm/mol}} \times 24.1 \times 10^{-3} \text{ m}^3\text{/mol} = 23 \times 10^{-6} \text{ m}^3\text{/m}^3$$

The result, 23 ppm, is very close to the nominal value of the injected concentration.

C. Injected SO_3: Quantity Accounted for in Stack Emissions

1. Emission as H_2SO_4 vapor

Concentrations of H_2SO_4 found in the outlet duct during conditioning tests were all less than 1 ppm. Such low values are to be expected as a result of the low gas temperature recorded at the sampling point 120°C (about 250°F), if one consults the dew point concentrations predicted by Banchero and Verhoff[4] (Figure 21). It is therefore evident that if SO_3 injection significantly increases

SO_4^{-2} emissions, the increase must be found in the composition of emitted particulates.

2. Emission of SO_4^{-2} in particulates

Data from cyclone samples. The soluble SO_4^{-2} concentrations in particulate collected in cyclones at the outlet duct during conditioning tests were individually 6.4, 6.3, and 7.6% or the average was 6.8% (Table 10). The average value was used with outlet particulate concentrations calculated from efficiency tests to compute equivalent concentrations of SO_3 lost to the stack in the solid phase as summarized in Table 12.

The soluble SO_4^{-2} content of outlet ash during the baseline test was 2.6%. The particulate concentration at this time was about 0.63 mg/l.* Thus, the corresponding SO_3 concentration without conditioning was 4.4 ppm, a value that exceeded each emission level given in Table 12 except those for Test 2-3, which is known to have given a faulty indication of the precipitator performance during conditioning. It is evident, therefore, that the total amount of SO_3 emitted in particulates was lower with conditioning than without as a result of the marked reduction in the mass concentration of particulates.

Data from filter samples. Computations of stack losses of SO_3 as particulate SO_4^{-2} found on the filters used in the efficiency tests gave the results summarized in Table 13. These results confirm the conclusion just given: an insignificant fraction of the injected SO_3 escapes to the stack as SO_4^{-2} in particulates.

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* This concentration is the average of two outlet determinations, expressed for a temperature of 21°C at a pressure of 1 atm, with water vapor present.

Table 12. Injected SO_3 Found
In Outlet Cyclone Samples of Ash

Test	Sampling Train[1]	Particulate Concentration[2], gm/m³	Corresponding SO_3 Concentration, ppm
2-1	ASME	0.092	1.6
	EPA	0.163	2.8
2-2	ASME	0.071	1.2
	EPA	0.098	1.7
2-3	ASME	0.318	5.4
	EPA	0.556	9.5
2-4	ASME	0.205	3.5
	EPA	0.210	3.6

1. Used for determination of total particulate concentration given in next column.

2. At 21°C and 1 atm. with water vapor present.

Table 13. Injected SO_3 Found
In Outlet Filter Samples of Ash

Test	Sampling Train	Particulate Concentration[1], gm/m^3	Corresponding SO_3 Concentration, ppm
2-1	ASME	0.092	1.2
	EPA	0.163	2.0
2-2	ASME	0.071	1.0
	EPA	0.098	0.8
2-3	ASME	0.318	3.3
	EPA	0.556	---[2]
2-4	ASME	0.205	3.3
	EPA	0.210	---[2]

1. At 21°C and 1 atm. with H_2O present.

2. Filter sample not available for analysis.

V. COMPUTER MODEL PROJECTIONS OF PRECIPITATOR PERFORMANCE

The SRI-EPA mathematical model[6] was used to analyze the performance of the precipitator during the test program and to estimate the plate area required for 99% collection efficiency without the aid of conditioning agent. In order to use the model to simulate the precipitator operation with high dust resistivity, it is necessary to estimate a "useful" input power from the voltage-current relationships. This is required because the model is based on the assumption that the input values of current and voltage represent a unipolar particle charging process in which all of the charge transported to the collecting electrode from the corona wires is carried by either corona current or the charged dust particles. The average conditions used were estimated from the voltage-current relationships obtained on March 27. The averages of the values selected for the TR sets are: 35kV applied voltage, 3.5 nA/cm^2 current density. Figure 23 presents results from the computer program in terms of overall collection efficiency as a function of specific collecting area. The theoretical performance is clearly much greater than the measured performance obtained by Research Cottrell on March 27. However, if the overall collection efficiency is reduced by empirical relationships which are intended to estimate the effects of gas sneakage, particle reentrainment, and nonuniform gas velocity distribution, fair agreement can be obtained by assuming a gas velocity distribution with a normalized standard deviation of 25%, and by further assuming that reentrainment and gas sneakage losses amount to 20% of the mass collected in each stage over three effective stages. The computer projection based on these assumptions is labeled curve 2 on Figure 23. These assumptions indicate that a specific collecting area of 78.8 $m^2/(m^3/sec)$ (400 $ft^2/1000$ ACFM) would result in 99.0% overall collection efficiency. However, this projection does not contain a safety factor for TR set failures, nor does it consider the possibility that the

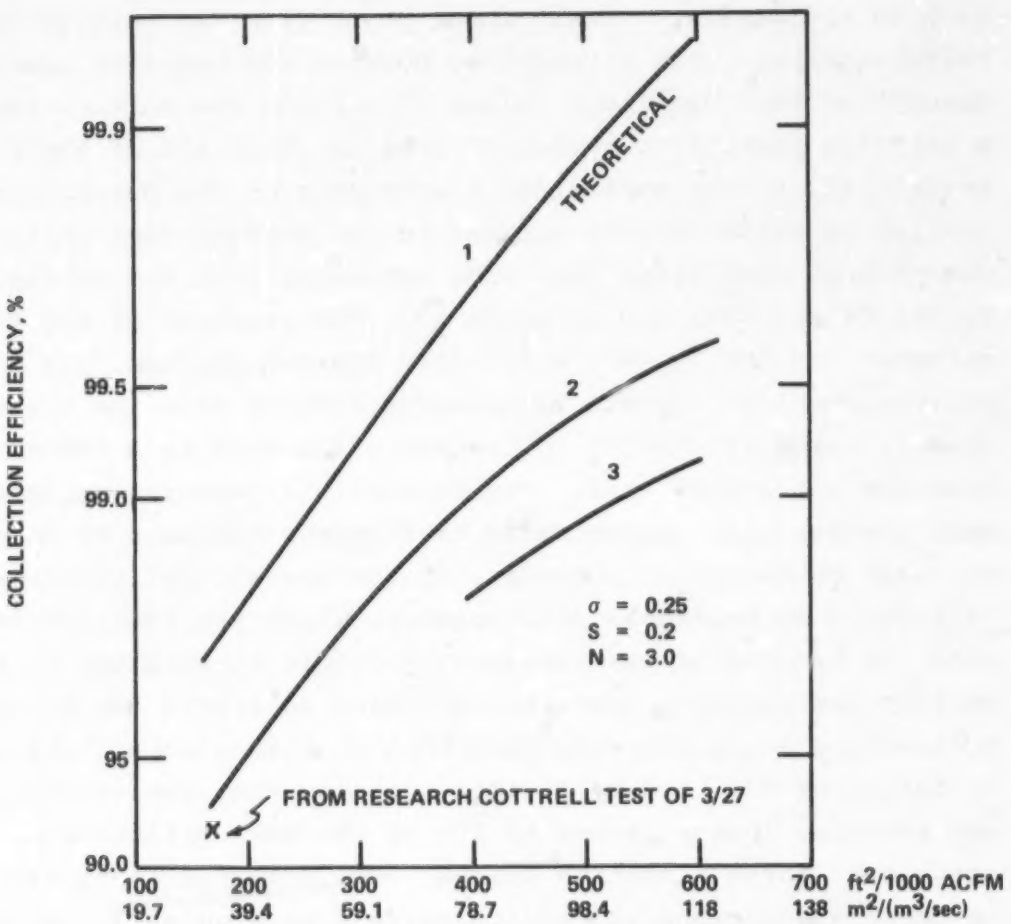

Figure 23. Computer Model Projections of Collection-Efficiency without SO_3

assumed electrical operating conditions may be degraded if dust resistivity increases. The latter consideration constitutes a major uncertainty since the electrical operating characteristics of the precipitator will be critically influenced by dust resistivity changes.

In an effort to obtain an estimate of specific collecting area which includes a safety margin, the following procedure was employed to obtain curve 3 on Figure 23: (1) The model was used to calculate the overall efficiency if the SCA were effectively reduced from 78.8 to 59.0 $m^2/(m^3/sec)$ (400 to 350 $ft^2/1000$ ACFM) in 1/2 of the precipitator. (2) The model was used to calculate overall efficiency if the SCA were reduced from 118 to 88 $m^2/(m^3/sec)$ (600 to 450 $ft^2/1000$ ACFM) in 1/2 of the precipitator. (3) The results from (1) were plotted at 78.8 $m^2/(m^3/sec)$ (400 $ft^2/1000$ ACFM), and the results from (2) were plotted at 118 $m^2/(m^3/sec)$ (600 $ft^2/1000$ ACFM). This procedure results in an estimated requirement of 108 $m^2/(m^3/sec)$, or 550 $ft^2/1000$ ACFM, to achieve 99% collection efficiency with a safety margin for transformer-rectifier failures as specified above.

Figure 24 gives the theoretical model projections and the reduced projections (using the same parameters for gas velocity distribution and reentrainment and sneakage as were used in Figure 23) with the average electrical operating conditions achieved with SO_3 conditioning. These results indicate that, with the measured size distribution and electrical operating parameters achieved during the SO_3 injection test, 99% collection efficiency is theoretically possible at the existing SCA. However, as stated earlier, additional testing is required to determine whether the SO_3 system will allow precipitator performance to remain at the 99% level for extended periods with a boiler load of 300 MW.

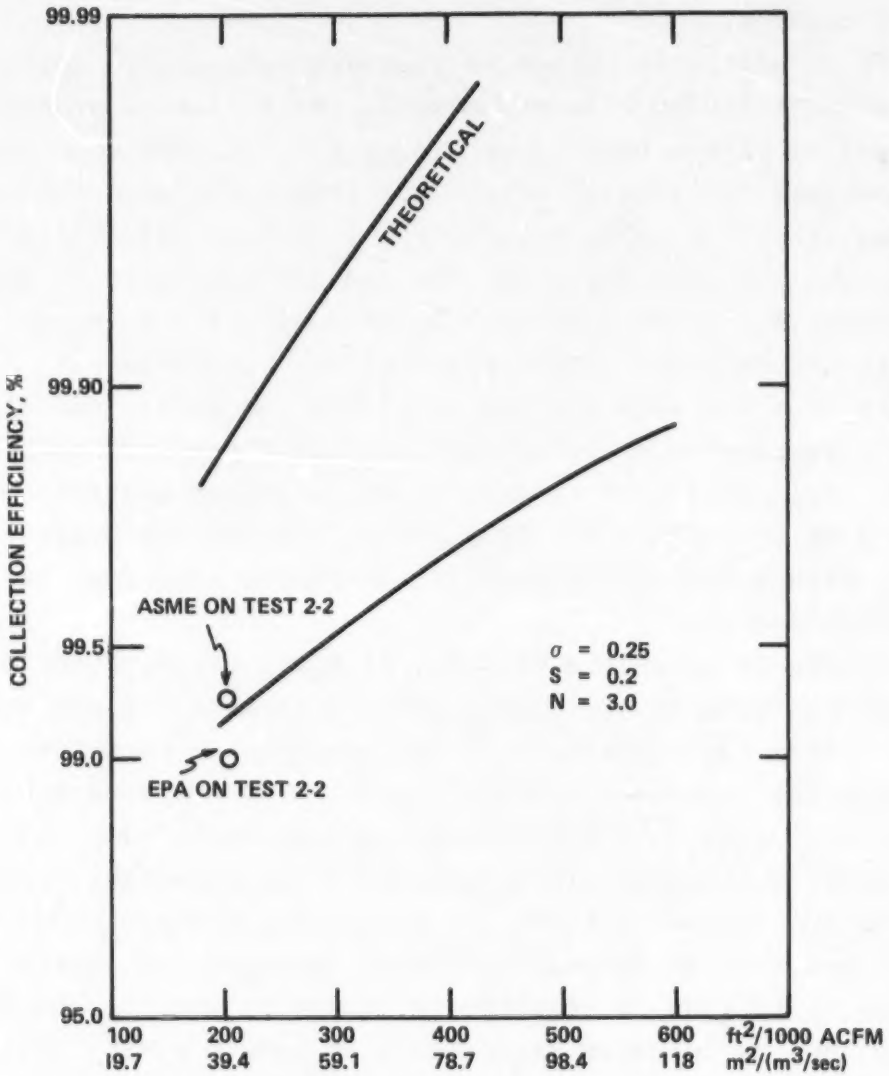

Figure 24. Computer Model Projections of Collection-Efficiency with SO_3

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